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Analysis of systematic differences from GPS-measured and GRACE-modeled deformation in Central Valley, California

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Abstract

Crustal seasonal displacement signals, which are commonly attributed to surface mass redistributions, can be measured by continuous GPS, modeled by GRACE and loading models. Previous studies have shown that the three methods generally agree with one another. However, the discrepancy among them in some regions has not yet been investigated comprehensively. In this paper, we compare the vertical annual displacement signals in the Central Valley, California derived from GPS, GRACE and loading models. The results show a general agreement from these three methods for most sites, which reach the maximum during the dry late summer and autumn. Irregular annual terms with peaks during the wet winter and spring are detected from GPS solutions for the sites located in places with extensive groundwater depletion. However, annual vertical variations for these same sites derived from GRACE and loading models reach the maximum in August and minimum in February. To explain such apparent discrepancy, we find that the vertical components of abnormal sites show a strong correlation with in situ groundwater data, which display peaks during cold months. In addition, with the assistance of water table depth data, we perform hydrological simulations based on Terzaghi's Principle, Mogi's Model and Green's function method. The results suggest that the discrepancy from GPS-measured and GRACE-modeled deformation is induced by the seasonal variations of groundwater.

Keywords: Crustal seasonal displacement; Discrepancy; GPS; GRACE

1. Introduction

With the rapid development of space geodesy techniques and surface mass loading models, the seasonal surface mass redistribution signals have been detected by surface displacement observations and gravity observations, and are confirmed by mass loading simulation models. Using global continuous GPS (Global Positioning System) time series and loading models, Dong et al. (2002) confirmed that ~40% of annual vertical variations for site positions are related to surface mass redistributions. Later, Davis et al. (2004) suggested that annual displacement over the Amazon River Basin measured by GPS and modeled by GRACE (Gravity Recovery and Climate Experiment) data show a high agreement that proved the feasibility of deriving crustal seasonal variations from GRACE. Recent studies have focused on the combination of GPS, GRACE and loading models to infer earth's annual deformation (Dong et al., 2006; King et al., 2006; van Dam et al., 2007; Tregoning and Watson, 2009; Tesmer et al., 2011; Fu et al., 2012; Fu and Freymueller, 2012; Nahmani et al., 2012; Demir and Dogan, 2014).

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Results from studies using GPS, GRACE, and loading models have concluded that the main contributors to seasonal surface displacement are changes in atmospheric surface pressure, non-tidal oceanic mass loading, and terrestrial water storage (soil moisture, snow, and groundwater). In addition, the magnitude of annual and interannual variations from the three methods shows a good agreement at the global scale (Tregoning and Watson, 2009; Tesmer et al., 2011). However, systematic differences (magnitude and phase differences in annual and subannual terms) in the results of the three methods still exist in some regions, which could be caused by geophysical processes and technique errors. For example, the discrepancy between GPS and GRACE results is related to the local hydrological loading effects in West Africa (Nahmani et al., 2012). The low spatial resolution of GRACE measurement is also a significant source contributor to this discrepancy (Khan et al., 2010).

More accurate results and interpretations of seasonal variations could be obtained through observation integration and global inversion of multiple techniques and models (Fu et al., 2013; Jin et al., 2013; Amos et al., 2014). To ensure the precision and accuracy from the multiple technique integration, however, the systematic differences between techniques and models must be carefully investigated.

The aim of this study is to explain the differences between GPS-measured and GRACE-modeled seasonal vertical variations in site positions. The study also uses loading models to provide additional information about the surface displacement caused by atmosphere, non-tidal ocean, snow and soil mass loading. We chose the Central Valley, California, as an example to examine the discrepancy between GPS and GRACE observations. The data setting and the comparison for earth's annual variations are presented in Section 2. Potential sources responsible to the discrepancy between GPS and GRACE derived displacement and potential deformation are explored in Section 3. In order to give a theoretical explanation for the discrepancy, hydrological surface displacement are simulated with Terzaghi's Principle, Mogi's Model and Green's function method. Finally, the groundwater mass redistribution effects in systematic differences in GPS and GRACE observations are summarized in Section 4.

2. Seasonal deformation in Central Valley, California

2.1. GPS, GRACE, and loading models

In this study, we used 60 daily GPS time series in Central Valley, California from 1996 to 2014 provided by the Scripps Orbital and Permanent Array Center (http://sopac.ucsd.edu/) to get the GPS vertical annual displacement signals.

We used the gravity components from GRACE Level-2 RL-05 solutions provided by CSR (Center for Space Research) from 2003 to 2014 (ftp://podaac.jpl.nasa.gov/allData/grace/L2/CSR). As we focus on the ground displacement, we need to transform GRACE gravity observations into surface mass variations (Wahr et al., 1998) and then we compute site position variations of each GPS stations following the procedure of Farrell (1972) with the load love numbers from the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981). Due to the uncertainties of GRACE stokes coefficients at high degrees (Wahr et al., 2004), we perform Gaussian smoothing with 350 km averaging radius to reduce the error. In order to compare the deformation from GPS and loading results, we include the GAC solutions (the atmosphere and ocean mass effects) to estimate the whole deformation induced by atmosphere, ocean, snow and soil. Since GRACE is unable to provide degree one terms (Davis et al., 2004), we replace those spherical harmonic coefficients with the results from Swenson et al. (2008). We also replace the C20 terms using with SLR results (Cheng and Tapley, 2004) because of the unreliability of C20 from GRACE. Lastly we compute the vertical deformations induced by mass redistributions derived from GRACE.

In addition, loading models of atmosphere, ocean, snow and soil are used to help to measure the well-known seasonal contributors' influences in this study. For the atmospheric pressure displacement, we use NCEP's (http://www.ersl.noaa.gov) 6-h sample, $2.5° \times 2.5°$ spatial resolutions. The 12-h sampling model, ECCO (Estimating the Circulation & Climate of the Ocean), is used to compute the surface displacement driven by non-tidal ocean effects and its spatial resolution is $1° \times 0.3–1.0°$. The widely used Noah land model (Ek et al., 2003) from GLDAS (Global Land Data Assimilation System) (Rodell et al., 2004), is chosen to calculate the surface displacement caused by soil and snow mass in this paper. The Noah model has a $1.0° \times 1.0°$ spatial resolution and 3-h sample interval. We use Green's functions (Farrell, 1972) based on the PREM Earth model (Dziewonski and Anderson, 1981) to calculate the displacement induced by mass loading changes. Since we concentrate on seasonal site variations, we smoothed modeled deformations with a 30-day moving average.

2.2. Seasonal deformations of permanent GPS stations

Seasonal displacement for permanent GPS stations from those three approaches are processed with QOCA (Quasi-observation Combination Analysis) software (Dong et al., 1998; Dong et al., 2002; Dong et al., 2006). As we mainly focus on annual variations in site positions, the word "seasonal" represents annual period only in this paper.

Vertical annual variations of Central Valley's dense GPS stations are shown in Fig. 1 with GPS, GRACE and loading models. The height of Central Valley shows strong seasonal variations. The vertical periodic variations, excluding GPS stations located in places with groundwater depletion, have similar phases in GPS data, GRACE, and loading models. The peaks occur during the dry summer and

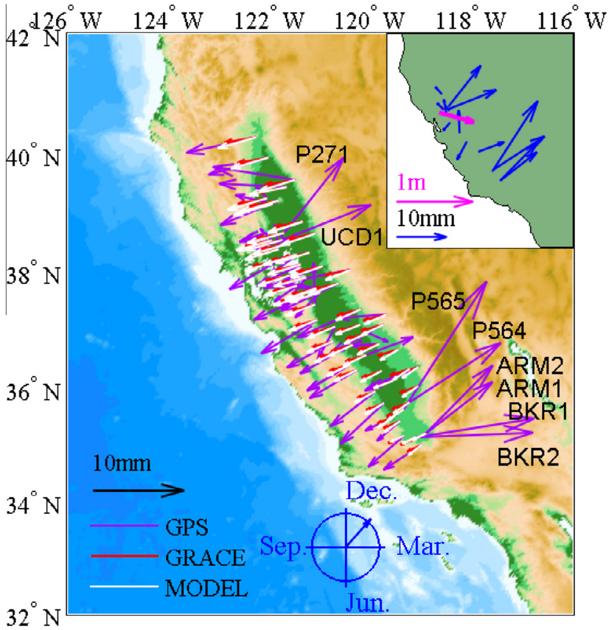

Fig. 1. Vertical annual terms of the 60 sites in Central Valley from GPS, GRACE, and loading models. The arrow's length represents the amplitude and the angular counted from east counterclockwise are phase. The seasonal term is defined as $A\sin(\omega(t\text{-}t_0) + \phi)$ with amplitude A and phase ϕ (phase is related to 1 January), where t_0 is 1990.0, ω is the annual angular frequency. The inset map shows the annual terms of abnormal GPS stations and water table variations of one well located in Sacramento Valley.

autumn in these GPS sites. Vertical annual amplitudes of the sites are <10 mm, the average amplitude from GPS is 5.11 mm. The average amplitude is 0.47 mm from GRACE, and 0.56 mm from loading models. Vertical displacements from the three methods agree well in phase in the sites surrounding the Central Valley but differ in magnitude. We have compared these results with Fig. 3 from Amos et al. (2014). It shows that seasonal peak uplift from the GPS sites surrounding the Central Valley during the dry summer and autumn, which is out of phase with the sites inside the Central Valley with massive groundwater depletion. We note that our vertical seasonal variation solutions agree in phase with the results from Amos et al. (2014), but our amplitudes are 2–3 mm larger than that from Amos et al. (2014). The magnitude difference would ascribe to GPS data analysis strategies.

GPS observations and loading models predictions of annual variations show similar phase at most sites. It helps to confirm that the actual geophysical processes of atmosphere circulation, non-tidal oceanic movement, and the hydrological cycle are the main sources to earth's seasonal variations. Those GPS stations are responding elastically to the addition or removal of surface loads. Annual terms for the GPS sites derived from GRACE further attribute the observed crustal seasonal variations to surface mass redistributions.

Contrary to the other GPS stations, the observed annual terms for sites ARM1_GPS, ARM2_GPS, BKR1_GPS, BKR2_GPS, P271_GPS, P565_GPS, P564_GPS and UCD1_GPS reach their maximums during January and February, and they are out of phase with the measurements from other GPS sites. Actually those GPS sites are on the top of aquifers, which will have a large poroelastic response due to the addition or removal of groundwater. The poroelastic effect caused site displacements due to underground mass variations are usually ignored. GPS measures the site displacements directly. We will demonstrate that the groundwater mass variations induce site displacements through both elastic and poroelastic effects in next subsection. Also, annual vertical variations in the sites from GRACE solutions and loading models are nearly inverse with GPS's results. We will explore this difference in Section 3.

2.3. Comparison with groundwater variations

The abnormal sites with phase discrepancies are all located in the center part of the Central Valley where extensive groundwater depletion has occurred in past years. The volume of groundwater lost has already caused serious land subsidence problems in Central Valley. The Central Valley is the largest groundwater basin in the United States. It is a synclinal trough filled with thick marine and continental sediments of late Cretaceous to Holocene. Originally its aquifer system was in balance through natural recharge and discharge. The favorable climate, rich water and fertile land have led to rapid growth of population in the 19th and 20th centuries. After 1900, the deficit between surface water supply and water demand led to groundwater resource pumping for irrigation, which caused serious water level decline and land subsidence. Since the 1970's the reduction in groundwater pumping has halted most of the water level decline. However, the land subsidence still continues in the Sacramento Valley, Tulare-Wasco and the Arvin-Maricopa areas, especially during dry years (Galloway et al., 1999; Faunt et al., 2009; Famiglietti et al., 2011; Scanlon et al., 2012; Sneed, 2012; Amos et al., 2014; Borchers and Carpenter, 2014).

As the abnormal sites located on the thick sediments, which will have a large poroelastic response due to the addition/removal of groundwater, we would like to explore the groundwater variation with the earth's surface motion. Fig. 2 depicts the vertical displacement of ARM1_GPS/ARM2_GPS from GPS measurements and water level changes in two wells that are adjacent to ARM1_GPS. For comparison, we give ARM1_GPS vertical component variations modeled from GRACE. Groundwater level changes of the two wells help explain the correlation between water table variations and earth's surface displacement. For sites ARM1_GPS and ARM2_GPS, land subsidence still continues from GPS estimation with a velocity about -14.87 mm/yr. However, GRACE result shows that ARM1_GPS moves upward with a velocity about 0.11 mm/yr. Previous studies show that land subsidence is an ongoing problem in Arvin-Maricopa areas, where

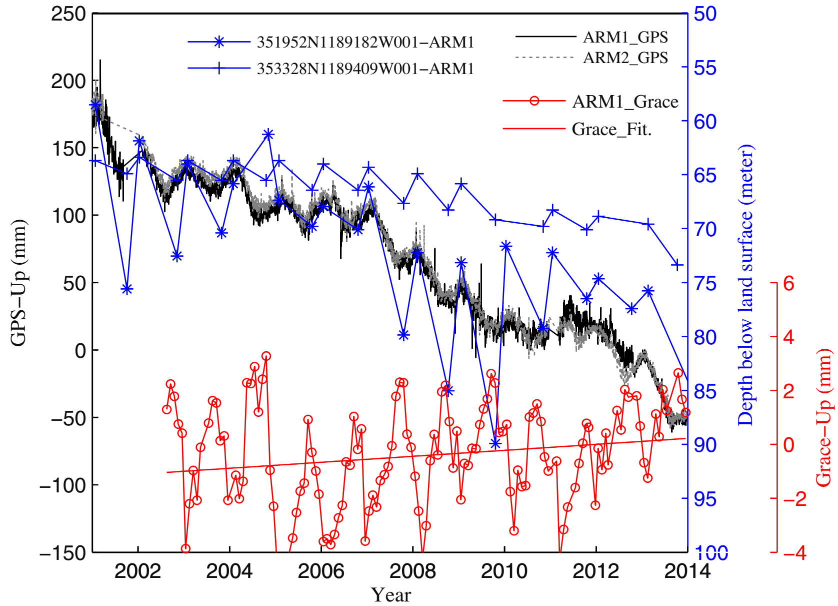

Fig. 2. Black and gray lines are GPS estimated vertical displacements of ARM1_GPS/ARM2_GPS. GRACE inverted vertical deformation for ARM1_GPS is the red line. Blue lines are groundwater level changes of two wells that are adjacent to ARM1_GPS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ARM1_GPS and ARM2_GPS are located (Borchers and Carpenter, 2014). Thus, we would like to confirm that GRACE modeled displacement has large modeling error in the two sites.

Besides, groundwater level changes from DWR (California Department of Water Resources) data base show a strong coincidence with GPS observed surface deformation (Fig. 2, blue lines). 351952N1189182W001 water well is located about 1 km away from ARM1_GPS, while well 353328N1189409W001 is about 10 km away. Both the two wells decline in recent years, corresponding with the subsidence recorded by ARM1_GPS from GPS solutions.

In addition, water table of well 351952N1189182W001 shows a great drop in the beginning in 2007. This could be related to the local rainfall of the area. Rainfall in Visalia (Fig. 3) was less than 5 mm during 2007, indicating this area was in drought. In the 1960s, a channel was built for water diversion from northern California to agricultural irrigation in central and southern California, underground aquifers in Arvin-Maricopa basin became the underground reservoir. In wetter years, excess water empties into underground aquifer storage; groundwater is extracted during drought years to provide the Los Angeles area with water. Therefore, when groundwater was extracted from aquifer, the water table went down in 2007. Hence, the decline of water table in 2007 was attributed to the drought. Meanwhile great subsidence also occurred in this time of ARM1_GPS from GPS estimation.

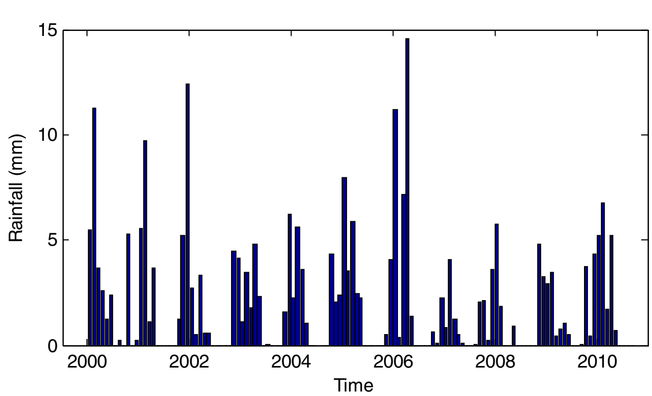

Fig. 3. Rainfall in Visalia from 2000 to 2010.

Groundwater is a vital component to hydrological cycle. Both the seasonal and long-term changes to groundwater can deform the earth's surface. Since the long-term variations to groundwater have induced the land subsidence in Arvin-Maricopa, there must be a correlation between groundwater elevation annual variations and seasonal vertical variations in site positions. Annual peak uplift for ARM1_GPS and ARM2_GPS occurs in the beginning of a new year from GPS, overlapping with the water table peaks in both two wells (Fig. 2). For the snow and surface water loads, which reach a maximum in cold month (Argus et al., 2014) will deform earth down in these months (Fig. 4). Then, snow and soil loads will not be the factors to the ARM1_GPS annual peak. Though the displacements caused by ocean and atmosphere are corresponding with the ARM1_GPS annul peak, the annual peaks are less than 1 mm, which means they cannot induce such strong seasonal surface deformation (Dong et al., 2002; Amos et al., 2014; Fig. 4). Therefore, we would like to attribute the water table variations in the aquifer to the source of seasonal and long-term variations to phase abnormal site ARM1_GPS.

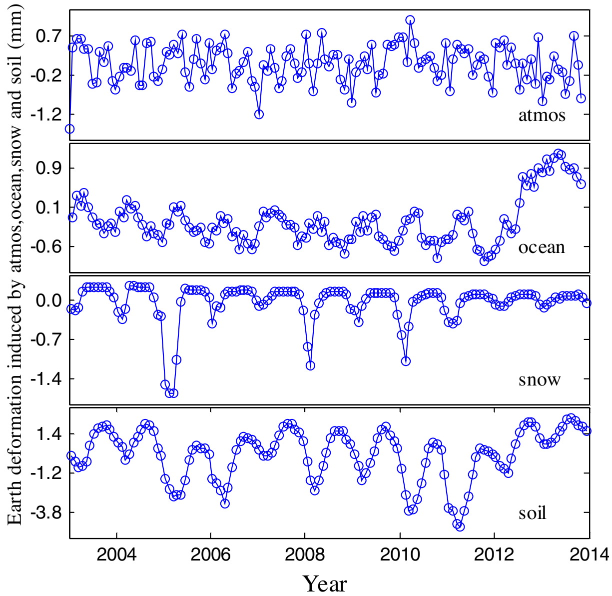

Fig. 4. Earth deformation of ARM1_GPS induced by atmosphere, ocean, snow and soil.

Now, we further explore the abnormal GPS site variations and their adjacent well data. As the abnormal sites are located in the Sacramento Valley, Tulare-Wasco and the Arvin-Maricopa areas, we discuss the three places separately. We compare the site variations of BKR1_GPS, BKR2_GPS located in Arvin-Maricopa, P271_GPS, UCD1_GPS located at Sacramento Valley and P565_GPS, P564_GPS located at Tulare-Wasco with their adjacent well data (Fig. 5). Besides, the well-known mass loadings induced surface displacements of BKR1_GPS, P564_GPS and P271_GPS are also shown in Fig. 5. As BKR1_GPS and BKR2_GPS, P654_GPS and P565_GPS, P271_GPS and UCD1_GPS show similar mass induced deformation from loading models, we only present BKR1_GPS, P564_GPS, P271_GPS deformations induced by atmosphere, ocean, snow and soil. The comparison result shows the same with ARM1_GPS, snow and soil induced deformation are opposite with the annual peaks of the two site while atmosphere and ocean effects is too small to cause the strong reverse phase in seasonal scale. Besides, the correlations of groundwater variations and GPS time series, confirm that the groundwater seasonal variations is the reason to the seasonal source contributor to the abnormal sites.

The site position seasonal variations of the abnormal sites modeled from GRACE and loading models peak during July and August (Figs. 1 and 2). Therefore, the phase of annual terms for the abnormal sites from GPS and GRACE/loading models are nearly inverse. Since the groundwater level variations are strongly correlated with the abnormal sites position variations, we would like to see whether the groundwater is the reason to induce the reverse variation between GPS measured and GRACE/loading model modeled deformation. For loading models, we are hard to provide an appropriate model about groundwater flow, which means we cannot provide quantitative deformation induced by groundwater. Hence, we mainly discuss earth's deformation from GPS and GRACE. The discrepancy between GPS observed and GRACE derived surface deformation will be discussed in detail in the next section.

3. What caused seasonal discrepancy between GPS-measured and GRACE-modeled surface deformation?

In this section, we investigate the source of systematic discrepancy between GPS-measured and GRACE-modeled surface displacements. First, we present the systematic discrepancy between seasonal-scale GPS observations and GRACE derived site positions. Then, using data from the USGS (United States Geological Survey) and DWR data base, we perform an analysis of the correlation between water table variations and the abnormal annual terms from GPS, GRACE surface displacements estimates. Finally, we use hydrological simulations to confirm the source of the discrepancy.

3.1. Comparison of annual water variations

Showing as Fig. 5, groundwater level changes are strong seasonal in most wells in Central Valley. Due to the lack of effective groundwater data, we obtained only two seasonal components of groundwater level changes in two well around the abnormal sites. The two wells are P271_GPS and UCD1_GPS, which are located in Yolo County in Sacramento Valley. To qualitatively depict the seasonal discrepancy between GPS and GRACE displacement estimation, we take the UCD1_GPS as an example to discuss here.

Using the same analysis as before, we obtained the periodic component of water table variations of well 001S004W25E005S from USGS data base (Fig. 1, inset map, magenta arrow). Fig. 6 gives the periodic variations for site UCD1_GPS from GPS, GRACE, loading models and annual water table variations of the well 50 km away from UCD1_GPS. The GPS observation peaks in late February while groundwater annual maximum occur in late March. They are out of phase with GRACE/loading models predicted surface displacement which uplift in late August. So, the maximum displacement in one year is totally 6-month difference between GPS and GRACE.

Since we have concluded that groundwater is the main contributor to abnormal sites' seasonal variations, we would like to explain the strong correlation between groundwater elevation and surface deformation from GPS and GRACE. It should be pointed out that both GPS and GRACE are sensitive to the total mass variations. But the contributions of surface mass and underground mass to surface displacements are different. And the relative contributions between surface loading and loading from groundwater to surface displacement cannot be determined without the use of separate hydrologic models.

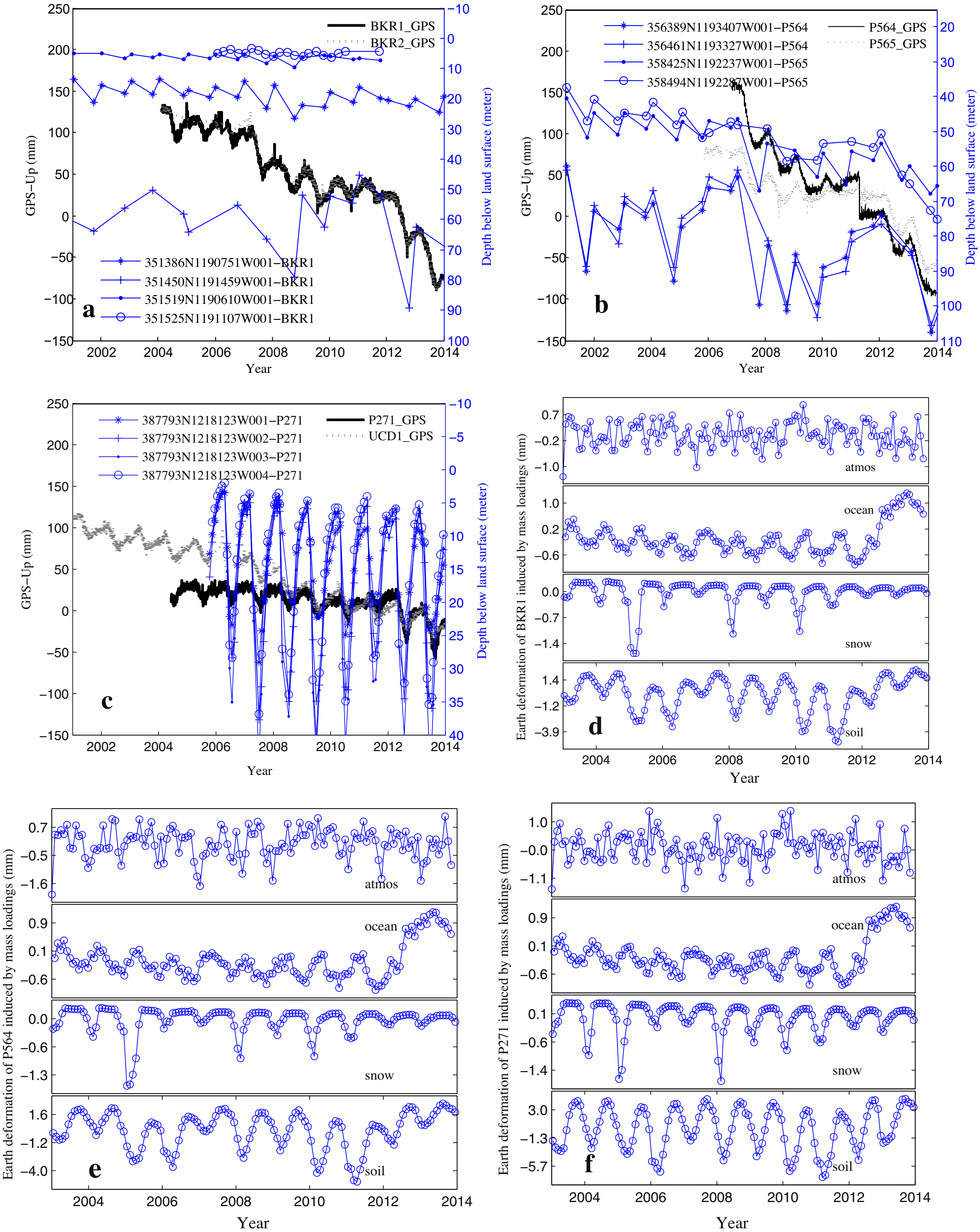

Fig. 5. (a) Black and gray lines are GPS observed vertical displacements of BKR1_GPS/BKR2_GPS. Blue lines are groundwater level changes of four wells that are adjacent to BKR1_GPS/BKR2_GPS. (b) Black and gray lines are GPS observed vertical displacements of P564_GPS/P565_GPS. Blue lines are groundwater level changes of four wells that are adjacent to P564_GPS/P565_GPS. (c) Black and gray lines are GPS estimated vertical displacements of P271_GPS/UCD1_GPS. Blue lines are groundwater level changes of four wells that are adjacent to P271_GPS/UCD1_GPS. (d) Earth deformation of BKR1_GPS induced by atmos, ocean, snow and soil. (e) Earth deformation of P564_GPS induced by atmos, ocean, snow and soil. (f) Earth deformation of P271_GPS induced by atmosphere, ocean, snow and soil. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

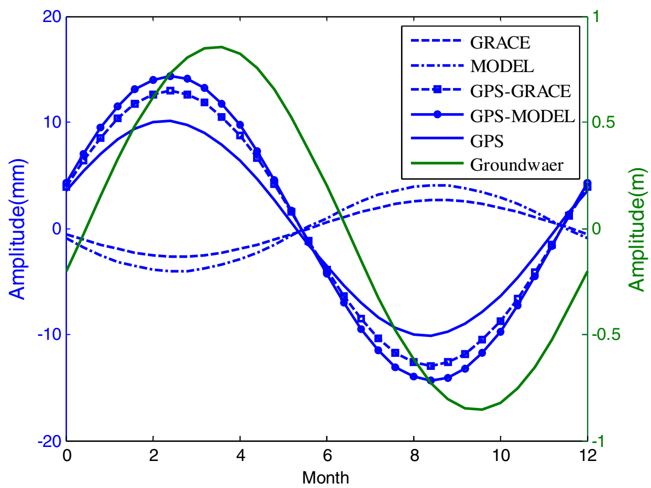

Fig. 6. Periodic vertical displacements of site UCD1_GPS given by GPS (solid line, blue), GRACE (dashed line), loading models (dash-dot line). The annual terms of UCD1_GPS that atmosphere loading, non-tidal oceanic loading, snow and soil loading have been removed from GPS (GPS-MODEL, dashed line with circle). Vertical periodic component that GRACE-derived displacement is subtracted from GPS solutions (GPS-GRACE, solid line with square). The solid line in green is groundwater annual variation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

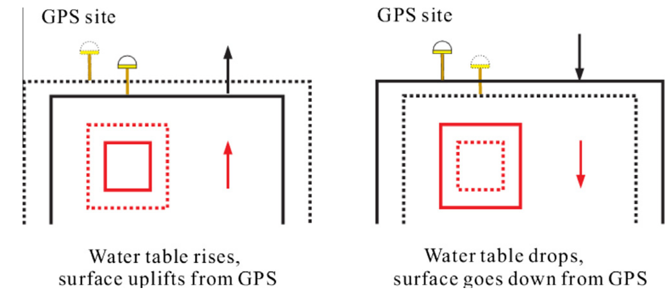

Fig. 7. Groundwater induced surface variations from GPS. Red squares are groundwater, and black lines represent surface. Besides, yellow semicircles are the GPS antennas. For left map, when groundwater level rises under surface (red dashed line), it uplift the surface from GPS results (black dashed line). In contrary (the right sketch), when groundwater drops (red dashed line), the ground (black solid line) would go down (black dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Thus, the discussion follows is on the assumption that all other factors, such as surface water, keep constant except groundwater.

As we know, crustal seasonal displacement induced by groundwater variations could be detected by GPS directly. The relationship between groundwater level variation and compression of aquifer system is derived from the effective stress principle proposed by Terzaghi (1943). Based on the theory, simulations of groundwater induced surface motions have been validated to be useful by comparing with GPS and InSAR data. Groundwater rise will uplift the surface, whereas groundwater depletion will induce land subsidence (Galloway et al., 1999; Bawden et al., 2001; King et al., 2007; Ji and Herring, 2012; Galloway and Sneed, 2013), which means GPS observations keeps consistent with the groundwater variation. Fig. 7 is a conceptualization of this process.

Several studies have shown that GRACE gravity observations can model the earth's annual displacement (Davis et al., 2004; van Dam et al., 2007; Schmidt et al., 2008; Tregoning and Watson, 2009; Tesmer et al., 2011; Fu et al., 2012; Fu and Freymueller, 2012; Nahmani et al., 2012). But, for GRACE, a discrepancy exists when comparing with GPS solutions for groundwater induced surface motions. GRACE senses the surface mass variations directly through the spherical harmonics of the gravitational field. Then the site displacements caused by the measured mass variations are calculated based on the elastic responses of the Earth to surface loads (van Dam et al., 2001). The mass variation induced surface deformation is calculated using the Green's function method, which represents the displacement caused by surface mass loading. When groundwater level rises in aquifer, mass increases on surface from GRACE, indicating a ground subsidence of earth's surface. In contrast, when groundwater level drops, mass reduces on surface from GRACE, suggesting an uplift of the earth's surface. Fig. 8 shows a conceptualization of the groundwater-induced deformation from GRACE.

Hence, the groundwater induced surface variations from GRACE modelling and GPS observation are totally opposite. Hydrological simulations in next subsection help to clarify the difference between GPS and GRACE that is induced by groundwater.

3.2. Estimated Vertical displacements due to Groundwater

In the previous section, we qualitatively demonstrated the opposite phase between mass loading induced surface motions and the deformation caused by groundwater beneath the surface. In this section, we will quantitatively simulate the groundwater induced surface changes to explain the discrepancy between GPS observed and GRACE modeled displacements.

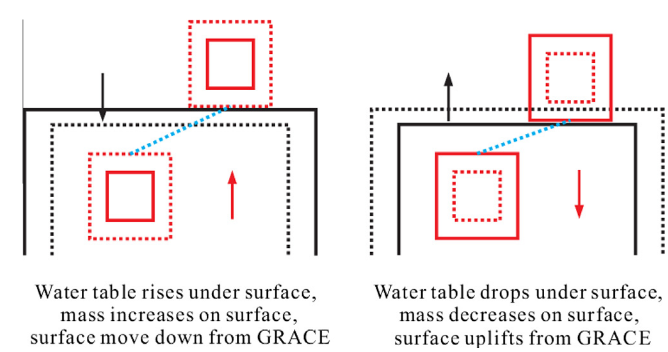

Fig. 8. Groundwater induced surface motions from GRACE. For left map, when groundwater rises under surface (red dashed line), mass increases on surface according to GRACE, the ground (black solid line) would goes down (black dashed line). In contrary (the right sketch), when groundwater drops (red dashed line), loss mass on surface from GRACE, the ground (black solid line) would uplift the surface (black dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As we know, load variations supported on the land will compress the elastic crust. Likewise, crust will rebound in response to the removal of mass. Methods that estimate the mass load produced static displacements of an elastic Earth are Terzaghi's Principle (Terzaghi, 1943; Bawden et al., 2001; King et al., 2007), Mogi's Model (Mogi, 1958; Cayol and Cornet, 1997; Lisowski, 2006) and Green's function method (Longman, 1962; Farrell, 1972; Mangiarotti et al., 2001). Terzaghi's Principle is the 1-D soil consolidation model. It describes the point response to point force on a free surface. Green's function approach shows the displacement field from a point mass load applied at the surface of an elastic half-space. Mogi's Model measures a point pressure source which effects on a uniformly pressurized cavity, isotropic elastic full-space.

3.2.1. Theoretical background

3.2.1.1. Terzaghi's Principle. The elastic response of the earth to the extraction of groundwater and replenishment is derived from the changes of pore fluid pressure in aquifer. One common theory to describe this influence is the one-dimensional soil consolidation theory propose by Terzaghi (1943), in which the porous deformation is assumed to be vertical (Galloway et al., 1998; Bawden et al., 2001; King et al., 2007). The theory gives the relationship between water head and vertical surface displacement. With the relationship of

$$\Delta b = -S_k \Delta h \tag{1}$$

vertical displacement Δb is computed. $-S_k$ is the storage coefficient in the aquifer, and Δh is change in head of groundwater level (King et al., 2007).

The storage coefficient of groundwater in aquifer has been esti mated by several investigators (Davis et al., 1959; Olmsted et al., 1961; Williamson et al., 1989; Galloway et al., 1999; Bawden et al., 2001; King et al., 2007). According the ratio of surface vertical displacement to groundwater elevation change, King et al. (2007) estimate the elastic storage coefficient as 0.0035. In our deformation simulation, we set $S_k = 0.0035$.

3.2.1.2. Mogi's Model. Mogi's Model is commonly used for volcanic deformation. As Terzaghi's Principle directly relates deformation with the groundwater table, we would like to use spherical sources of pressure, Mogi's Model (Mogi, 1958; Cayol and Cornet, 1997), to evaluate how the depth and volume variations of the water source impacts on displacement. On condition of spherical source's radius is much smaller than its depth d, the displacements (u, v, w) at point$(x, y, 0)$ would give as

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \Delta V \frac{1-v}{\pi} \begin{pmatrix} \frac{x}{R^3} \\ \frac{y}{R^3} \\ \frac{d}{R^3} \end{pmatrix} \tag{2}$$

where $R = \sqrt{x^2 + y^2 + d^2}$, ΔV is the change of source volume, v is Poisson's ratio the half-space.

In Central Valley, the thickness of the sediments ranges from 300 to 1000 m. Most of the freshwater is contained in the upper part of the sediments (Olmstead et al., 1961; Williamson et al., 1989). In order to keep consistent for the Central Valley aquifer system, the surface motion modelling are performed in a hypothetical of 1 km^2 areal groundwater basin, and vertically in thickness 500 m. The volume changes of the groundwater are head changes of water table at the 1 km^2 basin respect 2006.

3.2.1.3. Green's functions method. Another useful way to compute the earth deformation is Green's function approach, which is relate to a given load q_n at the earth surface. Then the surface vertical displacements u can be expressed as

$$u(\theta) = \frac{3}{\rho_e} \sum_{N=0}^{\infty} \frac{h'_n}{2n+1} q_n \tag{3}$$

where ρ_e is the earth's mean density, h'_n is the load love numbers, n is degree (Farrell, 1972; Mangiarotti et al., 2001). Besides, the load caused by continental waters is related to depth h of water through

$$q_n = \rho_{water} h \tag{4}$$

where the ρ_{water} is the water density.

Though Green's function method harmonizes well with the load on the earth's surface, we still give the groundwater induced deformation by Green's function method in order to compare the earth's motion and the simulated deformation from Green's function method. We use Green's functions (Farrell, 1972) based on the PREM Earth model (Dziewonski and Anderson, 1981) to calculate the deformation induced by mass loading changes. We perform the simulation with an area of 0.5cm^2.

3.2.2. Groundwater induced surface motions

In this section, we simulated the groundwater induced displacement with Terzaghi's Principle, Mogi's Model and Green's function method. The groundwater data is obtained from the DWR database (regardless of well depth or well use). We concentrate the vertical displacement on the point located where the well stands. The groundwater variations and three methods predicted surface motions are shown in Fig. 9. The water level declines more than 10 m from 2006 to 2015. Terzaghi's Principle gives a response of land subsidence to groundwater depletion. And the results from Mogi's Model are in good agreement with Terzaghi's Principle predictions. On the contrary, Green's function method, which is the same mechanism with GRACE deformation modelling, depicts a reverse effect that surface moves upward to response the groundwater decline. In addition, estimated annual component from Green's function method is out of phase with the two other methods.

We compare the predicted surface displacements around the well with its adjacent GPS site position variations of

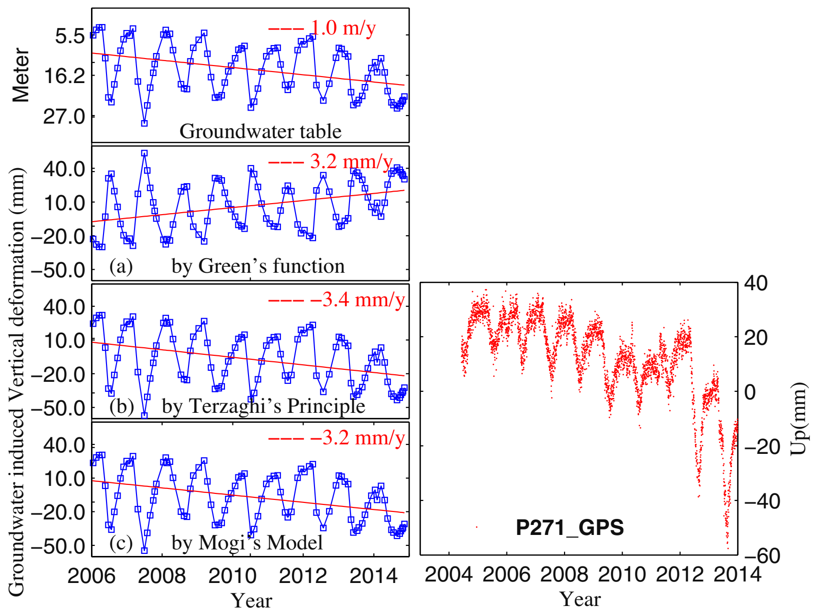

Fig. 9. Groundwater level changes of well 387793N1218123W001. Vertical displacements calculated by Green's function, Terzaghi's Principle, and Mogi's Model. And the height of site P271_GPS time series. (a) Deformations from Green's function method are performed with an area of 0.5cm^2. (b) The vertical displacement of land surface is computed using the Terzaghi's Principle with storage coefficient set as 0.0035 (no horizontal strains). (c) Vertical displacement of aquifer system pumping centers calculated with a square that length 1 km, the depth water source are set as 500 m, the volume variations of groundwater are respect to the stat time of 2006.

P271_GPS (Fig. 9). The well (38.77°N, 121.81°W) is about 10 km away from P271_GPS. Water changes in well induced surface changes predicted by the three theories are roughly measurements (regardless of the loading effects) of earth's surface displacements. The simulated motions gives the correlation between surface variations and groundwater elevation changes.

According to P271_GPS, land subsidence continue with a velocity of −4.1 mm/yr. And the result from Mogi's Model and Terzagih's Principle both show that the surface moves down with a velocity more than −3 mm/yr. The result means that the places where the well located decline more than 23 mm in the past nine year from 2006 to 2015. The observation from P271_GPS shows that land moves downward more than 36 mm in the same nine years. In general, the simulated surface changes from Mogi's Model and Terzagih's Principle is correlated with the observed site variations though slight difference still exists. It seems that the assumed origin from Mogi's Model and Terzaghi's Principle interpret well with the mass change under the earth's surface.

However, the groundwater induced surface displacements calculated by Green's function method is reverse with the result from Mogi's Model and Terzaghi's Principle. Result from Green's function method shows that the surface moves upward because of the water table decline of groundwater, whereas the predictions from Mogi's Model and Terzaghi's Principle show subsidence induced by groundwater. Thus, the long-term variations from GRACE is nearly reverse with Mogi's Model and Terzaghi's Principle prediction. According to P271_GPS GPS time series (Fig. 9), surface in this area goes down from 2004 to 2014. In seasonal scale, the prediction from GRACE reaches a maximum in July, and result from Mogi's Model and Terzaghi's Principle peaks in January. As discussed in Section 2.3, P271_GPS reach its peak in July. Then, we would like to conclude the abnormal GPS sites are influenced by poroelastic effects more than other sites.

According to the discussion, groundwater induced surface motions from Terzaghi's Principle and Mogi's model is consistent with GPS observations. And Green's function method, the mechanism of GRACE estimates modeling gives a reverse deformation prediction. The nearly inverse deformation information from hydrological simulations confirms that groundwater induced deformation from GRACE has large modeling errors with recent calculation strategy.

4. Conclusions

This paper exposes the difference between GRACE-modeled surface displacements and GPS-observed site position variations. Annual variations of some sites in the Central Valley from GPS observations correctly reflect the underground water induced deformation (Fig. 1). Observations from GPS is nearly inverse with GRACE and loading models estimations in places with extensive groundwater depletion. Although, the lack of GRACE spatial resolution still exists in our modeled displacement, hydrological simulations assist to confirm the source of this discrepancy. Estimated deformation induced by groundwater in Terzaghi's Principle and Mogi's Model is consistent with GPS measurements. Though Green's function method derived deformation may be opposite with the actual movements of crust, it demonstrates the technologies difference between GRACE and GPS.

Due to the inherent correlation between the elastic surface displacement and the mass loading variations, the GPS, GRACE solutions and the geophysical models are commonly used to infer the mass redistributions from surface displacement measurements or vice versa (Kusche and Schrama, 2005; Wu et al., 2012; Argus et al., 2014). For the surface displacements caused by underground mass like groundwater and magma, the poroelastic effect is dominant in the near-field above the aquifer or magma chamber, and the elastic effect becomes dominant in far-field. Thus the well-known Green's function method is suitable for the inversion of underground mass distribution only for far-field stations (Argus et al., 2014). Problems may also exist for underground mass inversion from surface displacement in the near-field, in which may also lead an inverse result from GPS and GRACE. We leave this problems for future investigation.

Seasonal coordinate variations measured by geodetic techniques contain various geophysical processes, as well as some systematic errors at seasonal periods, such as the draconitic error in GPS series (Ray et al., 2008). However, observed unusual seasonal terms in Central Valley still provide an opportunity to explore the systematic differences between techniques. The abnormal seasonal terms open a door to make a further investigation of the underground geophysical activities.

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