

Dear Anonymous Referee #1,

Thanks very much for your constructive comments concerning our manuscript entitled “Detecting seasonal and long-term vertical deformation in the North China Plain using GRACE and GPS”. Those comments are all valuable and very helpful into revising and improving our paper, as well as the important guiding significance to our researches. We have studied comments carefully and here replied each comment bellow. The original comments are in plain text and the replies in italics which we hope meet with approval.

Anonymous Referee #1 (Received and published: 18 November 2016)

In this manuscript, the authors present the time series variation of vertical displacement in North China Plain using GPS and GRACE data. Also, they analyzed the impact of Terrestrial Water Storage loss on vertical displacement. Generally, the manuscript is written clearly and illustrates some interesting results about the long-term variation of vertical displacement in North China Plain from 2003 to 2013 and discussion about the impact factors of vertical displacement like TWS loss. However, the manuscript suffers some deficiencies that need to be discussed before publishing the manuscript. The major points that need to be added are provided below.

1) Surface vertical displacement and estimation of water storage variation using GRACE data were presented in many researches during recent years and the methodology are more or less the same. However, there is little discussion in validation of the result. In this study, is there any field measurement data of groundwater level for validation of the water storage loss in NCP?

>Linsong Wang et al.: Thank you very much for the good comments. You mentioned that our result needs more discussions based on measurement data of groundwater level in NCP. We have acquired in situ groundwater level measurements (most of groundwater table depth in the shallow unconfined aquifers, available from 2002 to 2013), which mainly locating in the central and eastern plain of the NCP (including the Beijing, Tianjin and some cities of Hebei, Henan and Shandong province). The data series are obtained from Ministry of Water Resources of China (available at: <http://sqx.hydroinfo.gov.cn/shuiziyuan/>). In the revised manuscript, we will get the area-weighted mean groundwater level change series in the NCP from time series of monthly groundwater table depth changes of 20 cities in our study region. Using the mean time series of

monthly groundwater level data, we can do a comparison between monthly groundwater storage (GWS) variations estimated from GRACE minus GLDAS/Noah model and monthly groundwater level changes observed by monitoring wells after multiplying by mean value of specific yields in the NCP during 2002-2012 (Fig. R1). Besides, according to the good comments of the Referee #2, we are also going to compare the depletion in TWS or GWS between our results and previous studied results (e.g., Huang et al., 2015; Feng et al., 2013; Moiwo et al., 2013; Tang et al., 2013; Su et al., 2011) in the NCP. We believe these discussions can validate the GWS loss in the NCP.

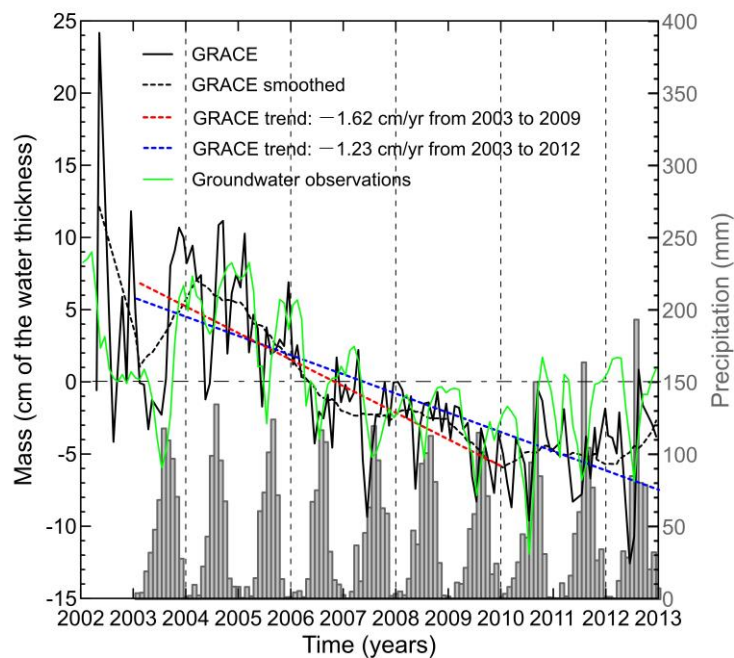


Figure R1. Time series showing total terrestrial water storage (TWS) changes in the spatially averaged area (kernel) of the NCP estimated from GRACE data and groundwater storage (GWS) variations from monthly groundwater level changes observed by monitoring wells.

2) In part 5.2, GPS trend changes of water storage are different in two periods (2004-2009 and 2010-2013), especially the long-term trend rate is different in different areas from 2010 to 2013. Are there any field measurement data of groundwater levels or groundwater used in different areas can support this result? In my opinion, the manuscript would be more improved if some groundwater data can be combined into this research.

> *Linsong Wang et al.: Thank you again. Before response this comment, we would like to explain why using GPS data after removed GRACE-derived deformations to detect long-term vertical deformation in the NCP. The detailed reasons are as follows.*

1) The GPS is now widely used in the geosciences for the estimation of precise station coordinates. The placement of a load on the Earth's surface causes deformation of the underlying solid Earth and displacements of its surface. GPS measurements of those displacements can provide information about the load.

2) Some previous studies have focused on the vertical component of crustal motion. These researches rely on the accurate interpretation of GPS motion in terms of surface stress or tectonic movement, and the deformation signal from surface mass loading is a source of noise. In these applications, they would like to obtain reliable loading models or even surface mass observations, which can be used to reduce the environmental loading contributions to the GPS observations. For some surface loads, such as the atmosphere, the loads are currently modeled to a fairly high degree of accuracy (van Dam et al., 1994). However, for other loads, especially the distribution of water mass on continents (soil moisture, groundwater, snow and ice) the load is poorly known in most regions of the globe, but the deformation it causes is large enough to contribute to the GPS signal (van Dam et al., 2001). Fortunately, with the development of GRACE, the mass variations from hydrologic loading now can be quantitatively estimated. The GRACE-derived time-variable gravity field coefficients can be converted to harmonic coefficients for crustal deformation in three components.

Next, please see our detailed responses below.

1) As shown in Figure 8a in our manuscript, the obvious uplift are presented in the decomposition of the signal based on the GRACE-derived TWS trend, which showed the long-term mass loss in the NCP from 2003 to 2009, but the rate of this decrease slowed towards the end of 2009 and then increases again after 2010. This may explain the differences of GPS trend changes of water storage in these two sub-periods. In addition, in situ groundwater level measurements also confirmed the difference of trend changes of GWS in these two sub-periods that you mentioned "GPS trend changes of water storage are different in two sub-periods (2004-2009 and 2010-2013)" (Fig. R1).

2) However, the water mass loss trend from GRACE or in situ data is inconsistent with the GPS results in our study, which you mentioned 'especially the long-term trend rate is different in different areas from 2010 to 2013'. The groundwater level changes from observations of shallow aquifers shows a persistent increase after 2010, when the annual precipitation begins to increase (Fig. R1). Obviously, the recharges from precipitation for deep aquifers are different with the shallow aquifers. In addition, these discrepancies may reflect uncertainties in GRACE, land surface models (LSMs) and groundwater monitoring well data. It also can explain the different GRACE-derived uplift caused by total GWS change (GRACE minus GLDAS/Noah) in different stations from 2010 to 2013 (Fig.8b in manuscript).

In fact, it is more important about the applicability of loading theory in the NCP. The previous studied results showed that the groundwater depletion occurs in the shallow unconfined aquifers in Piedmont Plain while groundwater depletion occurs in the deep confined aquifers in the central and eastern plain of the NCP. Especially in the central and eastern plain of the NCP, although some GPS can detect land subsidence due to the occurrence of groundwater depletion in the deep confined aquifers, but the loading deformation effect from mass change is still remain in GPS long-term trend. Thus, we compute the GRACE-derived long-term trend from the CSR solutions for all continuous GPS sites used in this paper. The results indicate GRACE-derived an overall uplift for the whole region at the 0.37~0.95 mm/yr level from 2004 to 2009, but the rate of change direction is inconsistent in different GPS stations at -0.40~0.51 mm/yr level from 2010 to 2013 (Table 1 in manuscript). Then we remove this hydrological-induced long-term trend from GPS actual observed vertical rates to derive the corrected vertical velocities (Figure 9 in manuscript), which can be used to study the vertical crust movement caused by single tectonic movement (fault activity or land subsidence).

Merry Christmas and Happy New Year!

Best regards,

Linsong Wang et al.

25 December 2016