1 **Detecting seasonal and long-term vertical displacement in the North**

2 **China Plain using GRACE and GPS**

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13

14 **Abstract:**

15 Twenty-nine continuous Global Positioning System (GPS) time series data together with data

16 from Gravity Recovery and Climate Experiment (GRACE) are analyzed to determine the

17 seasonal displacements of surface loadings in the North China Plain (NCP). Results show

18 significant seasonal variations and a strong correlation between GPS and GRACE results in

19 the vertical displacement component; the average correlation and Weighted

20 Root-Mean-Squares (WRMS) reduction between GPS and GRACE are 75.6% and 28.9%

21 respectively when atmospheric and non-tidal ocean effects were removed, but the annual

22 peak-to-peak amplitude of GPS (1.2~6.3 mm) is greater than the data (1.0~2.2 mm) derived

23　from GRACE. We also calculate the trend rate as well as the seasonal signal caused by the

24　mass load change from GRACE data, the rate of GRACE-derived Terrestrial Water Storage

25　(TWS) loss (after multiplying by the scaling factor) in the NCP was 3.39 cm/yr (equivalent to

26　12.42 km^3/yr) from 2003 to 2009. For a 10-year time span (2003 to 2012), the rate loss of

27　TWS was 2.57 cm/yr (equivalent to 9.41 km^3/yr) which is consistent with the groundwater

28　storage (GWS) depletion rate (the rates loss of GWS were 2.49 cm/yr and 2.72 cm/yr during

29　2003~2009 and 2003~2012, respectively) estimated from GRACE-derived results after

30　removing simulated soil moisture (SM) data from GLDAS/Noah model. We also found that

31　GRACE-derived GWS changes are in disagreement with the groundwater level changes from

32　observations of shallow aquifers from 2003 to 2009, especially between 2010 and 2013.

33　Although the shallow groundwater can be recharged from the annual climate-driven rainfall

34　(e.g., the groundwater level changes from observations of shallow aquifers show a persistent

35　increase after 2010 when the annual precipitation begins to increase), but the important facts

36　indicate that GWS depletion is more serious in deep aquifers. Basing on spherical harmonic

37　coefficients for the gravity field and load Love numbers, we use GRACE model to remove the

38　vertical rates of elastic displacements due to the surface mass changes from GPS data. The

39　GRACE-derived result shows an overall uplift in the whole region at the 0.37~0.95 mm/yr

40　level from 2004 to 2009, but the rate of change direction is inconsistent in different GPS

41　stations at –0.40~0.51 mm/yr level from 2010 to 2013. Then we removed the uplifted vertical

42　rates which are induced by TWS from GPS-derived data to obtain the corrected vertical

43　velocities caused by tectonic movement and human activities. The results show that there are

44　uplift areas and subsidence areas in NCP. Almost the whole central and eastern region of NCP

45   suffers serious ground subsidence caused by the anthropogenic-induced groundwater

46   exploitation in the deep confined aquifers. In addition, the slight ground uplifts in the western

47   region of NCP are mainly controlled by tectonic movement (e.g., Moho uplifting or mantle

48   upwelling).

49

50   **Keywords:** GPS, GRACE, Seasonal and long-term displacement, Terrestrial water storage,

51   the North China Plain

52

53   **1. Introduction**

54   Using Global Positioning System (GPS) to monitor crustal motion, especially in the vertical

55   or height component due to its large amplitude, which has been used to study surface loading

56   caused by mass change. Site-position time series recorded by continuous GPS arrays have

57   revealed the vertical displacement variations resulted from trend or seasonal distribution of

58   mass in a region or global changes (e.g., a change of continental water [Bevis et al., 2005; van

59   Dam et al., 2007; Wahr et al., 2013], ice [Sauber et al., 2000; Khan et al., 2010; Nielsen et al.,

60   2013], snow [Heki, 2001; Grapenthin et al., 2006], ocean [van Dam et al., 2012; Wahr et al.,

61   2014] and atmospheric mass [van Dam et al., 1994; Boehm et al., 2007]).

62

63   On the global scale, terrestrial hydrologic mass exchanges that causes significant large-scale

64   loading occur between the oceans, continents, and atmosphere at seasonal and inter-annual

65   time scales. On the local scale, for the inter-annual and long-periodic change in the hydrologic

66   cycle, what significantly affects loading are large anthropogenic disturbances on groundwater

67 extraction and artificial reservoir water impoundment and other climate-driven factors (e.g.,

68 natural floods and droughts) [e.g., Chao et al., 2008; Rodell et al., 2009; Feng et al., 2013;

69 Joodaki et al., 2014; Wang et al., 2014]. The global-scale mass variations closely related to

70 changes in terrestrial water storage (TWS) are observed by the Gravity Recovery and Climate

71 Experiment (GRACE) satellite mission, while the surface elastic displacement can be

72 estimated if the load and rheological properties of the Earth were known [Farrell, 1972]. The

73 majority of previous loading studies solved the three components of crustal motion by

74 adopting joint analysis of GRACE time-variable gravity field coefficients and GPS data

75 [Kusche and Schrama, 2005; van Dam et al., 2007; Fu and Freymueller, 2012; Fu et al., 2013].

76 In principle the loading effects caused by the majority of mass redistributions near the Earth's

77 surface are from water, atmospheric, and ocean transports on daily to inter-annual timescales

78 [Kusche and Schrama, 2005]. The contribution to the surface displacement made by the

79 variations of the atmospheric and ocean can be reasonably modeled by using global

80 atmospheric surface pressure data and space geodetic data respectively. Thus, after removing

81 the loading effects of the atmospheric and ocean, GRACE-derived displacement and GPS data

82 allow the detection of changes in the Earth's larger hydrological storage systems.

83

84 In general, changes in TWS capacities depend on precipitation and human consumption.

85 Variations in TWS may be related to precipitation which is strongly driven by climate and can

86 be simulated from global water and energy balance models [Syed et al., 2008]. This is related

87 to soil texture and root depth in the case of soil water storage (e.g., soil moisture and

88 vegetation canopy storage can be derived from the Global Land Data Assimilation System

89 (GLDAS) [Rodell et al., 2004], the WaterGAP Global Hydrology Model (WGHM) [Döll et al.,

90 2003] and the Community Land Model (CLM) [Oleson et al., 2013]), surface water storage

91 (e.g., water in rivers, lakes, reservoirs and wetlands can be derived from WGHM while snow

92 or ice can be derived from WGHM and CLM), and naturally occurring (i.e., climate-driven)

93 aquifer storage (e.g., groundwater predicted by WGHM and CLM). Variations in TWS may

94 also be caused by man-made factors, such as water withdrawals for irrigation purposes [Döll,

95 2009] and dam construction for power generation and navigation [Wang et al., 2011]. These

96 changes in TWS can be observed in situ (i.e., groundwater level and impounded water level).

97 The TWS integrated by all the variations can lead to the overall changes in crust

98 displacement.

99

100 This study focuses on the crustal deformation of the North China Plain (NCP) (Figure 1),

101 which is one of the most uniformly and extensively altered areas by human activities in the

102 world [Tang et al., 2013]. The NCP is one of the world's largest aquifer systems and supports

103 an enormous exploitation of groundwater. Overexploitation of groundwater has seriously

104 affected agriculture irrigation, industry, public supply, and ecosystems in the NCP. Previous

105 studies used GRACE data, land surface models, and well observations to provide insight on

106 groundwater depletion in the NCP [Su et al., 2009; Zhong et al., 2009; Feng et al., 2013;

107 Moiwo et al., 2013; Tang et al., 2013; Huang et al., 2015]. Liu et al. [2014] has discussed

108 loading displacement in the NCP before. Only five GPS stations (i.e., BJFS, BJSH, JIXN,

109 TAIN, and ZHNZ) data are used in their work. Although they calculated the seasonal

110 amplitudes, phases and trends of vertical displacement from GRACE and GPS, the

111 atmospheric and non-tidal ocean loading effects were not removed in the Liu et al.'s work, i.e.,

112 they added the Atmosphere and Ocean De-aliasing Level-1B (AOD1B) solution (GAC

113 solution) back to the GRACE spherical harmonic solutions.

114

115 Here, we use GRACE and data from 29 GPS sites to study the seasonal and long-term loading

116 displacement due to dynamic hydrological processes and groundwater-derived land

117 subsidence in the NCP. In contrast to previous focus study [Liu et al., 2014], the most obvious

118 difference between our results and their work is we removed other loading effects (e.g.,

119 atmospheric and non-tidal ocean) in order to reflect the seasonal and long-term displacement

120 caused by TWS loads better. Additionally, we discuss long-term trend due to mass change

121 revealed by GRACE measurements and its impacts on tectonic vertical rates evaluations.

122

123 **2. Data Analysis**

124 **2.1 GRACE Data**

125 The GRACE mission design makes it particularly useful for time-variable gravity studies.

126 GRACE was jointly launched by NASA and the German Aerospace Center (DLR) in March

127 2002 [Tapley et al., 2004a]. The Level-2 gravity products consist of sets of complete spherical

128 harmonic (Stokes) coefficients out to some maximum degree and order (typically $l_{max} = 120$)

129 averaged over monthly intervals. When considering large-scale mass redistribution in the

130 Earth system on a timescale ranging from weekly to interdecadal, it is reasonable to assume

131 that all relevant processes occur in a thin layer at the Earth's surface [Kusche and Schrama,

132 2005]. In this analysis, we assume that the gravitational and geometrical response of the Earth

133 can be described by Farrell's [1972] theory, where the loads Love numbers only depend on

134 the spherical harmonic degree. Thus, the elastic displacements due to the surface mass change

135 can easily be represented in terms of spherical harmonic coefficients for the gravity field and

136 load Love numbers, k_l, l_l, and h_l [Wahr et al., 1998; Kusche and Schrama, 2005]. Level-2

137 products are generated at several project-related processing centers, such as the Center for

138 Space Research (CSR) at the University of Texas, GeoForschungsZentrum (CSR) in Potsdam,

139 Germany, and the Jet Propulsion Laboratory (JPL) in California. The mass estimates (TWS

140 and sea level) show very good agreement among these products [Fu and Freymueller, 2012;

141 Wahr et al., 2014; Wang et al., 2014].

142

143 This study used monthly sets of spherical harmonic (Stokes) coefficients from GRACE RL05

144 (i.e., Release 5) gravity field solutions generated from the CSR, spanning from February 2003

145 to April 2013. Each monthly GRACE field consisted of a set of Stokes coefficients, C_{lm} and

146 S_{lm}, up to a degree and order (l and m) of 60. In fact, the GRACE Stokes coefficients ("GSM"

147 coefficients denoted by the GRACE Project) have had modeled estimates of the atmospheric

148 and oceanic mass signals removed. Thus the GRACE coefficients include the full terrestrial

149 water storage signal with remaining atmospheric and oceanic signals due to errors in the

150 respective models [Swenson et al., 2008]. Generally, using the GRACE AOD1B products can

151 add back the de-aliasing atmospheric and non-tidal oceanic effects to the GRACE data.

152 However, we would like to reduce the environmental loading contributions to the GRACE

153 and GPS observations, if we study on the accurate interpretation of displacement due to TWS

154 loading. Thus, we analyzed the effects of non-tidal ocean variations and atmospheric loading

155 on the GRACE model and GPS coordinates, please see Section S1 in the supporting

156 information for details.

157

158 We replaced the GRACE C_{20} coefficients with C_{20} coefficients inferred from satellite laser

159 ranging [Cheng et al., 2013]. Due to the fact that the reference frame origin used in the

160 GRACE gravity field determination is the Earth's center of mass (CM), GRACE cannot

161 determine the degree-1 terms variations in the Earth's gravity field (geocenter motion). Here,

162 we used degree-1 coefficients as calculated by Swenson et al. [2008] to determine the position

163 of the CM relative to the center of figure (CF) of the Earth's outer surface. We applied the

164 post-processing method described in Swenson and Wahr [2006] to remove north-south stripes.

165 We adopted 250 km as the averaging radius to implement Gaussian smoothing, a technique

166 which suppresses errors at high degrees [Wahr et al., 1998; van Dam et al., 2007]. Stokes

167 coefficients resulted from A et al. [2013] were used to remove contributions from Glacial

168 Isostatic Adjustment (GIA). The contribution of GIA is about 0.28~0.33 mm/yr and

169 non-seasonal in the NCP, which is small and non-seasonal; so their impact on the seasonal

170 results discussed in this paper would be minimal, even if they were not removed.

171 The spatial pattern of TWS, shown in Figure 2, was obtained from monthly GRACE mass

172 solutions for NCP and surrounding regions between spring, 2003, and spring, 2013. An

173 obvious negative trend was identified localized over North China, including some of the

174 Northwest regions (i.e., Shanxi province) and Northeast regions (i.e., Liaoning province). The

175 TWS changes derived from the GRACE data show significant loss trends across the entire

176 study area (NCP), specifically in Beijing, Tianjin, Hebei province, and Shanxi province.

177 Previous studies have investigated how much groundwater depletion has caused the

178 GRACE-derived TWS loss in the whole of the NCP [Su et al., 2009; Feng et al., 2013; Moiwo

179 et al., 2013] or in different sub-regions of the NCP [Zhong et al., 2009; Tang et al., 2013;

180 Huang et al., 2015]. These investigations, however, did not focus on regional displacement

181 due to seasonal or long term variations of hydrologic loading.

182

183 **2.2 GPS Data**

184 Twenty-four GPS sites from the Crustal Movement Observation Network of China

185 (CMONOC) and five GPS sites from the International GNSS Service (IGS) (Table 1) were

186 analyzed in this study (Figure 1 shows the locations of the GPS stations). Eight GPS sites of

187 them were located in the surrounding area of the NCP. Daily values for the upward, eastward

188 and northward coordinates were determined by GPS data of IGS stations between 2003 and

189 2013, which is consistent with GRACE time span. The 24 GPS sites of CMONOC provided

190 data from 2010 to 2013. GIPSY/OASIS-II (Version 5.0) software was used in point

191 positioning mode to obtain the daily coordinates and covariances; these were used to

192 transform the daily values into ITRF2008 [Altamimi et al., 2011]. We estimated this daily

193 frame alignment transformation using a set of reliable ITRF stations (~10 stations each day).

194 In the GPS processing, corrections for solid Earth tides were undertaken, and ocean tide

195 loading effects were corrected using ocean tide model FES2004 with Greens Functions

196 modeled in the reference frame of CM (center of the mass of the total Earth system) to

197 maintain theoretical consistency and adherence to current IERS conventions [Hao et al., 2016;

198 Fu et al., 2012], but atmospheric pressure loading or any other loading variations (non-tidal

199 ocean loading) with periods > 1 day were not removed. In order to focus on the seasonal and

200 trend feature over the entire observation time, we first smoothed the data to reduce large

201 scatter before using a 3-month-wide moving window filter to remove the short-period terms.

202

203 Due to the coseismic displacement of the 2011 Mw9.0 Tohoku earthquake, we estimated and

204 removed offsets (i.e., using the differences of the average values of seven days between

205 before and after earthquake to obtain the coseismic displacement) at those times for the

206 vertical time series of GPS stations at Eastern China. Wang et al. [2011] study results reveal

207 that the coseismic horizontal displacements induced by the earthquake are at the level of

208 millimeters to centimeters in North and Northeast China, with a maximum of 35 mm, but the

209 vertical coseismic and postseismic displacements are too small to be detected. In order to

210 maintain consistency with the GIA effects presented in the GRACE solutions, we remove GIA

211 effects for all GPS stations by using Stokes coefficients (l=100) results computed by A et al.

212 [2013] which used the ICE5G ice history and VM2 viscosity profile [Peltier et al., 2004].

213

214 Figure 3a shows the time series (2003~2012) of daily solutions for IGS GPS sites BJFS,

215 ZHNZ, BJSH, JIXN and TAIN. The long-term linear trends are mainly dominated by surface

216 mass loading and tectonic processes, and the GPS time series shows significant seasonal

217 variations. The peak-to-peak seasonal amplitude can be seen to be more than 20 mm which

218 reflects the strong seasonal mass changes in the NCP. The GRACE data from CSR uses model

219 output to remove the gravitational effects of atmospheric and oceanic mass variability from

220 the satellite data before constructing monthly gravity field solutions. In order to compare the

221   displacement from GPS with GRACE, the effects of atmospheric and non-tidal oceanic

222   loading on the GPS coordinates needed to be removed. Displacements due to atmospheric

223   loading were calculated using data and programs developed by the GGFC (Global

224   Geophysical Fluid Center) (T. van Dam, NCEP Derived 6 hourly, global surface

225   displacements at $2.5° \times 2.5°$ spacing, http://geophy.uni.lu/ncep-loading.html, 2010). These

226   utilized the NCEP (National Center of Environmental Protection) reanalysis surface pressure

227   data set. The 12-hour sampling model, ECCO (Estimating the Circulation & Climate of the

228   Ocean, http://www.ecco-group.org/), is used to compute the surface displacement driven by

229   non-tidal ocean effects and its spatial resolution is $1° \times 0.3\text{-}1.0°$, i.e., 1 degree longitude (zonal)

230   interval and 0.3 to 1.0 degree in latitude (meridian) intervals from equator to high latitude. An

231   example of the effects of the non-tidal ocean and atmospheric loading in the GPS and

232   GRACE data is provided in the supporting information (Figure S1).

233

234   The displacements caused by atmospheric pressure and non-tidal ocean loading mainly show

235   seasonal fluctuations and no obvious long-term trend during GPS observation (e.g., time

236   series of height from atmospheric and non-tidal ocean loading at IGS sites in Figure 3b). The

237   annual amplitude is 4.0~4.6 mm and 0.24~0.42 mm for the atmospheric and non-tidal ocean

238   loading effects respectively, while the semi-annual amplitude is about 0.3 mm and 0.03 mm

239   respectively. But the phases between the atmospheric and non-tidal ocean loading effects have

240   more apparent difference. The results of the seasonal amplitudes and phase fits of vertical

241   displacements, derived by GRACE and GPS for IGS stations between before and after

242   correcting atmospheric and non-tidal ocean, are summarized in Table S1 in the supporting

243   information.

244

245   **2.3 Elastic Displacements Due to Mass Loads**

246   GRACE Stokes coefficients [Wahr et al., 1998] and load Love numbers [Farrell, 1972] can be

247   used to estimate the displacement effects in three components (Up, North and East) caused by

248   mass load changes. The mathematical relationships [Kusche and Schrama, 2005; van Dam et

249   al., 2007] between the radial surface displacement (Up or Height) and the Stokes coefficients

250   of mass is:

251    $$\Delta h = dr(\theta,\phi) = R\sum_{l=1}^{N_{max}}\sum_{m=0}^{l}\tilde{P}_{l,m}(\cos\theta)\cdot(C_{lm}\cos(m\phi)+S_{lm}\sin(m\phi))\frac{h_l}{1+k_l} \qquad (1)$$

252   where Δh is the displacement of the Earth's surface in the radial direction at latitude θ (theta)

253   and eastward longitude ϕ (phi); N_{max}=60, R is the Earth's radius; $\tilde{P}_{l,m}$ is fully normalized

254   Legendre functions for degree l and order m; C_{lm} and S_{lm} are time variable components of the

255   (l,m) Stokes coefficients for some month; and h_l, k_l and l_l are the three degree dependent load

256   Love numbers which are functions of Earth's elastic property. In this equation we adopted the

257   load Love numbers provided by Han and Wahr [1995].

258

259   Similarly, horizontal displacements (North and East) can be calculated using the following

260   equations:

261    $$\Delta n = dr(\theta,\phi) = -R\sum_{l=1}^{N_{max}}\sum_{m=0}^{l}\frac{\partial}{\partial\theta}\tilde{P}_{l,m}(\cos\theta)\cdot(C_{lm}\cos(m\phi)+S_{lm}\sin(m\phi))\frac{l_l}{1+k_l}, \qquad (2)$$

262    $$\Delta e = dr(\theta,\phi) = \frac{R}{\sin\theta}\sum_{l=1}^{N_{max}}\sum_{m=0}^{l}\tilde{P}_{l,m}(\cos\theta)\cdot m(-C_{lm}\sin(m\phi)+S_{lm}\cos(m\phi))\frac{l_l}{1+k_l}, \qquad (3)$$

263   where *Δn* and *Δe* are north and east components of the displacement respectively, both

264   having positive values when the crust moves towards the north and east respectively. As is

265   mentioned in Section 2.1 above, in order to be consistently comparable to the GPS time series,

266   we corrected the degree-1 components to GRACE-derived mass variations, using Stokes

267   coefficients derived by Swenson et al. [2008]. With corresponding to degree-1 contribution to

268   vertical displacement, the value of load Love numbers of the degree-1 in the CF frame should

269   be computed by using equation (23) in Blewitt [2003].

270

271   Figure 4 shows an example (site BJFS, JIXN, TAIN and ZHNZ) of the GRACE-derived

272   vertical (Figure 4c) and horizontal displacements (Figure 4a and 4b) before and after

273   destriping. It can be clearly seen that the maximal amplitude of vertical displacement is

274   several order of magnitude higher than horizontal displacements. In addition, the calculated

275   results using the monthly GRACE model data after destriping show that the effects of TWS

276   (soil moisture, etc.) on surface displacements are seasonal variations and long-term changes

277   on vertical and horizontal components. As most of the stations are located in areas of TWS

278   loss in the NCP (see sites location in Figure 2), the fact is that the motion is upward (see the

279   positive trend of GRACE-derived vertical in Table 1) during this event (if a load is removed,

280   the site uplifts and moves away from the load [Wahr et al., 2013]). Identified horizontal

281   displacements are important as they constrain the location of load changes [Wahr et al., 2013;

282   Wang et al., 2014]. The displacement of the ZHNZ site is upwards and to the south (see the

283   negative trend of the ZHNZ north component in Figure 4a) due to the mass loss almost due

284   north of the site. Correspondingly, the displacement of the TAIN site is upwards and to the

285   southeast (see the negative trend of the north component and the positive trend of the east

286   component of the TAIN site in Figure 4a and 4b) caused by the mass loss located to the

287   northwest of the site, based on the use of GPS horizontals for loading studies from Wahr et al.

288   [2013].

289

290   **3. GRACE-derived Seasonal Variations and Comparison with GPS Measurements**

291   Using equation (1) and GRACE-derived Stokes coefficients, the vertical displacements at the

292   GPS sites in the NCP and its surrounding region can be calculated. To focus on these changes,

293   GRACE-derived vertical displacements were computed by fitting a model with a linear trend

294   and annual periodic terms using Least-Squares method over the entire 11 year time span, for a

295   comparison to the seasonal variations observed by GPS (Table 1). Figure 5 shows time series

296   of vertical displacements for GPS sites of IGS stations (BJFS, BJSH, JIXN, TAIN and ZHNZ).

297   The fitting results show the GRACE-derived (without ADO1B) peak-to-peak annual

298   amplitudes can be more than 2 mm, and the semi-annual amplitude are also visible at these

299   five GPS sites. This reflects the climate-derived seasonal hydrological fluctuations in the

300   NCP.

301

302   Compared with GRACE results mainly due to the mass change in seasonal and long-term

303   linear period, all GPS time series show significant seasonal and long-term trends which are

304   mainly dominated by tectonic and hydrological process. The fitting results (after

305   Least-Squares fitting) show the peak-to-peak vertical seasonal displacements from GPS time

306   series are to be larger than GRACE-derived results at those GPS sites, and the peak-to-peak

- 14 -

307   seasonal amplitude changes between 5 mm and 6 mm (Table 1). The results of the comparison

308   between GPS and GRACE-derived seasonal height variations at 24 GPS sites from

309   CMONOC can be seen in Figure S3 in the supporting information. For all the selected GPS

310   sites, the annual component is more dominant than the semi-annual one. The peak-to-peak

311   annual amplitude is 1.2~6.3 mm and 1.0~2.2 mm for the GPS and GRACE solutions,

312   respectively, while the semi-annual amplitude is about 1/2~1/3 times of that in annual

313   amplitude. These more consistent seasonal variations of GRACE and GPS height time series

314   reflect the climate-derived seasonal hydrologic process, i.e., heavy monsoonal precipitation in

315   the late summer months result in mass loads increase (the maximum negative of vertical

316   amplitude) and largely pumping for agricultural usage in late spring months cause mass loads

317   decrease (the maximum positive of vertical amplitude). The facts show that GPS data

318   relatively has a larger amplitude than GRACE-derived displacements, which does not merely

319   exist in the IGS stations but also almost all CMONOC stations except SXGX (Table 1). This

320   indicates that GPS has a strong sensitivity for local surface loading. By contrast, because the

321   spatial resolution of GRACE data is limited to approximately 300 km (N_{max}=60),

322   GRACE-derived results are mainly constrained by large scale areas. This means that

323   GRACE-derived vertical displacements show a small difference between stations due to the

324   results are averaged over scales of several hundred km or more.

325

326   Next, we compare GPS observed and GRACE-derived seasonal height variations. The

327   estimated annual amplitudes and initial phases derived from GPS (grey vector) and GRACE

328   (red vector) are shown in Figure 6. We find that there are many sites where the signals

329 disagree in both amplitude and phase. The annual amplitudes and phases from

330 GRACE-derived results are much more spatially coherent than those determined from the

331 GPS heights because GRACE solutions truncate to l_{max}=60 and the Gaussian filtering was

332 used to lead to so smooth out concentrated loads. The phase results of the GRACE-derived

333 displacements show that the annual signal peaks basically appear between September and

334 October, which indicates a maximum load occurs in this two months (summer monsoon).

335 However, there are several differences between the results of GPS and GRACE in some sites,

336 more specifically, the signal peaks sometimes appear between August and September

337 according to GPS data. The five signals of sites in the northwest foothills region of NCP agree

338 in phase, while annual amplitudes from GRACE are significantly less than GPS, e.g., NMTK,

339 NMZL, HEYY, HEZJ and HECC. The cause of most phase inconsistency may be the different

340 spatial resolution of GRACE compared to GPS. That is, GPS measurements can sense the

341 difference between loads very near the site, and loads a bit further away, but GRACE with

342 wavelengths on the order of 300 km reflects this variation at a monthly scale. Another

343 important reason is that a one-month sampling of GRACE means a phase sampling of 30°,

344 while a one-day sampling of GPS means a phase sampling of ~1°, the different temporal

345 sampling rate caused the inconsistent phase between GRACE and GPS.

346

347 With the purpose of quantitatively evaluating the consistency between GPS and GRACE, we

348 remove GRACE-derived seasonal displacement from GPS observed detrended height time

349 series to compute the reductions of Weighted Root Mean Squares (WRMS) based on the

350 equation (2) in van Dam et al. [2007]. Correlation between GPS and GRACE derived

351 seasonal variations and WRMS reduction ratio of remove GRACE-derived seasonal

352 displacement from GPS observed detrended height time series, please see the Table S3 in the

353 supporting information for details. All the selected sites show high correlation (85%~99%,

354 without TJBH site) when atmospheric and non-tidal ocean effects was not removed. By

355 contrast, the seasonal amplitudes and phases from GRACE results are much more spatially

356 coherent than those determined from the GPS heights, caused by the different spatial

357 resolution between them. In addition, we also attempt to calculate GRACE-derived horizontal

358 displacement using equations (2) and (3), and compare it with the GPS measurements. An

359 example (five IGS sites) of the comparison between GRACE-derived and GPS observed

360 horizontal displacements was presented to demonstrate the correlation of seasonal horizontal

361 variation caused by surface hydrological load. Please see the Figure S4 in the supporting

362 information.

363

364 **4. Long-Term Uplift Caused by TWS Loss**

365 **4.1 Compare Groundwater Storage (GWS) Variations With in-situ Measurements and**

366 **Previous Results**

367 To estimate TWS changes averaged over the NCP, an averaging kernel based on a calculation

368 that using weighted Gaussian convolution to construct monthly time series from GRACE

369 Stokes coefficients described by equation (5) of Wahr et al. [2014] was used. This method

370 extends the averaging kernel convolution approach [Swenson and Wahr, 2002] by allowing

371 for nonuniform weighting during the convolution. We took the NCP "basin function" from the

372 China provincial boundary grid points and we convolved with a 250 km Gaussian smoothing.

373   We then applied this averaging kernel to GRACE Stokes coefficients to obtain a TWS time

374   series for NCP (Figure 7). The results identified a continuous decrease in TWS from 2003 to

375   2009; the rate of this decrease slowed towards the end of 2009. The rate of TWS loss obtained

376   by this analysis was 1.62 cm/yr from 2003 to 2009 and 1.23 cm/yr from 2003 to 2012 (Table

377   2).

378

379   The estimated results for the time series analysis also include some contributions outside the

380   NCP due to the finite number of harmonic degrees in the GRACE solution (e.g., l_{max}=60 for

381   CSR solutions). The average kernel in our study is also not an exact unity cover for the entire

382   NCP area; these two factors result in under- or overestimation of the true TWS time series

383   signal. To estimate this ''leakage in'' signal, a scaling factor method was used to restore the

384   amplitude-damped TWS time series. This method, as described by Wahr et al. [2014], requires

385   the construction of a set of simulated Stokes coefficients which represents the signal from a

386   uniformly distributed 1 cm water depth change over the NCP. This estimates a water

387   volume=3.6626 km^3 based on the overall area of "basin function" (i.e., 366260 km^2). By

388   applying our GRACE analysis procedure to these simulated Stokes coefficients, we can infer

389   an average water thickness change equal to 0.47 cm for the NCP. Each monthly GRACE

390   estimate of NCP water thickness is then multiplied by a scaling factor=1 (cm)/0.47 (cm) to

391   obtain variations in the total water thickness per area of the NCP. Multiplying the monthly

392   GRACE estimates of NCP water thickness by a scaling factor=3.6626 (km^3)/0.47 (cm)

393   provides a mass change of the NCP. Table 2 shows the rate of GRACE-derived TWS loss

394   (after multiplying by the scaling factor) in the NCP was 3.39 cm/yr from 2003 to 2009; this is

395   equivalent to a volume of 12.42 km^3/yr. For a 10-year time span, the rate was 2.57 cm/yr,

396   which is equivalent to a volume of 9.41 km^3/yr.

397

398   In our study, the GRACE-based TWS time series covers water change at all depths: surface

399   water storage, soil moisture, snow and groundwater, including anthropogenic effects (i.e.,

400   groundwater withdrawal, inter-basin diversion, reservoir and coal transport). To isolate the

401   groundwater contributions, the Noah version of GLDAS which possesses monthly intervals

402   and spatial resolution of 1.0 degrees [Rodell et al., 2004] was used to subtract monthly water

403   storage estimates predicted by land surface models. GLDAS generates a series of land surface

404   forcing (e.g., precipitation, surface meteorology and radiation), state (e.g., soil moisture and

405   temperature, and snow), and flux (e.g., evaporation and sensible heat flux) data simulated by

406   land surface models. The GLDAS/Noah model can provide values of snow, vegetation and all

407   soil moisture layers, but it does not include anthropogenic and climate-driven groundwater

408   depletion. So we isolated GWS variations by subtracting simulated SM data from

409   GLDAS/Noah model from GRACE-derived total TWS.

410

411   In order to confirm validation of the results in this study, our GRACE-based estimate was

412   compared with field measurement data of groundwater level (e.g., in situ water table

413   observations) and the results from previous studied (e.g., the reported TWS loss from Zhong

414   et al. [2009], Su et al. [2011], Moiwo et al. [2009], and the reported GWS loss from Huang et

415   al. [2015], Feng et al. [2013], Tang et al. [2013]). We have acquired in situ groundwater level

416   measurements (most of groundwater table depth in the shallow unconfined aquifers, available

417   from 2002 to 2013), which are mainly located in the central and eastern plain of the NCP

418   (including the Beijing, Tianjin and some cities of Hebei, Henan and Shandong province). The

419   data series are obtained from Ministry of Water Resources of China (MWR) (available at:

420   http://sqqx.hydroinfo.gov.cn/shuiziyuan/). We get the area-weighted mean groundwater level

421   change series in the NCP from time series of monthly groundwater table depth changes of 20

422   cities in our study region. We also collected the daily precipitation data (rainfall amount) for

423   weather stations during the period of 2003~2012 from China Meteorological Data Sharing

424   Service System (CMDSSS) (available at: http://cdc.cma.gov.cn/index.jsp). Figure 7 shows our

425   GRACE-based estimate is generally consistent with that monthly groundwater level changes

426   observed by monitoring wells after multiplying by mean value of specific yields in the NCP

427   during 2002~2012.

428

429   Note that our GRACE-based TWS time series covers all depth of water mass changes and

430   most of the groundwater level changes from observations of shallow aquifers, which showed

431   the long-term mass loss in the NCP from 2003 to 2009, but the rate of this decrease slowed

432   towards the end of 2009 and then increases again after 2010. This difference in two

433   sub-periods (2004~2009 and 2010~2012) is mainly induced by climate-driven precipitation

434   recharge in NCP (Figure 7). In addition, comparison between monthly GWS variations

435   estimated from GRACE minus GLDAS/Noah model and in situ groundwater level

436   measurements also confirmed the difference of trend changes of GWS in these two

437   sub-periods (Table 2). The rate of GRACE-derived GWS loss (after multiplying by the

438   scaling factor) in the NCP was 2.49 cm/yr from 2003 to 2009 and 2.72 cm/yr from 2003 to

439　2009; this is equivalent to a volume of 9.12 km^3/yr and 9.96 km^3/yr, respectively. Our

440　GRACE-based depletion of groundwater was significantly higher than ground-based

441　measurements. Although the shallow GWS increase from 2010 to 2012 due to precipitation

442　recharge in NCP, but the increase of rainfall is difficult to recharge the current more serious

443　depletion of groundwater in the deep aquifers.

444

445　In addition, we compare the depletion in TWS or GWS between our results and previous

446　studied results. Table 2 shows our results and compare them with the earlier analysis in

447　different zones where TWS or GWS loss surveys have been published. We found that the

448　trend rate of our GRACE-based GWS in the whole NCP region is in good agreement with that

449　reported by Huang et al. [2015] during 2003~2012 and Feng et al. [2013] during 2003~2010,

450　which are estimated from the level 2 Release-05 GRACE data and multiplied by the scaling

451　factor. However, other previous results showed obvious difference between the loss rate of

452　TWS and GWS because these studies used the early versions of the GRACE data, different

453　defined area of NCP or do not use scaling factor compared with Huang's, Feng's and our

454　study. For instance, Zhong et al. [2009] found a rate of 2.4 cm/yr from 2003 to 2007 based on

455　level 2 Release-04 GRACE data in Beijing, Hebei and Tianjin; Su et al. [2009] calculated

456　TWS and GWS declining at a rate of 1.1 cm/yr and 0.5 cm/yr from 2002 to 2010, respectively,

457　based on level 2 Release-04 GRACE data in Beijing, Tianjin, Hebei, Shandong, and Henan;

458　and Moiwo et al. [2013] estimated a TWS loss rate of 1.68 cm/yr from 2002 to 2009 in the

459　vast north China (i.e., in addition to Beijing and Tianjin, the study area is comprised of 12

460　other provinces). Although Tang et al. [2013] did not applied scaling factor to restore the

461   amplitude-damped GRACE signal, but they used the latest GRACE products (RL05) and

462   same region of NCP with our study. Thus, Tang et al. [2013] estimated a GWS depletion rate

463   of 0.84 to 1.4 cm/yr (2003~2011) is also in good agreement with our estimated result before

464   being multiplied by scaling factor (i.e., the rate of TWS loss was 1.23 cm/yr from 2003 to

465   2012).

466

467   **4.2 Groundwater Depletion Contributions to Long-Term Uplift**

468   Loading or unloading of the crust from surface mass changes will cause the crust to subside or

469   uplift with different amplitudes. These displacements depend on the amplitude of the load and

470   the distance between the load and the observation point [Farrell, 1972]. On this basis, we used

471   GRACE-derived vertical displacements (the method of elastic displacements due to mass

472   loads described by Section 2.3) to evaluate TWS loss contributions for the evident crustal

473   uplift in the GPS measurements. Time series of monthly predicted vertical surface

474   displacements from GRACE for 25 GPS sites in the NCP were plotted (Figure 8a). The fitting

475   results (after Least-Squares fitting) show the trend rate of GRACE-derived vertical

476   displacements for the whole region at the 0.37~0.95 mm/yr level from 2004 to 2009, but the

477   rate of change direction is inconsistent in different GPS stations at –0.40~0.51 mm/yr level

478   from 2010 to 2013 (Table 1). The smoothed results indicate a rising trend from 2004 to 2012

479   (Figure 8a) which represented the TWS loss in the observation time span. Figure 8a also

480   clearly shows mass anomaly due to TWS changes in the vertical component, e.g., a notable

481   negative peak from 2003 to 2005 and subsidence in 2012 (grey background in Figure 8a).

482   These GRACE-derived long-term height fluctuations mainly include variations in the storage

483   of natural surface water: high storage in wet years and low storage in dry years [Tang et al.,

484   2013], which can be modeled using land surface model output such as those provided by the

485   GLDAS [Rodell et al., 2004].

486

487   Figure 8b shows the GRACE-derived height amplitudes after removing the continental water

488   storage signal which uses the output from the GLDAS/Noah hydrology model. The calculated

489   results show that the contributions of other types of TWS effects (except groundwater) on the

490   surface are small relative to groundwater depletion, and those main loading effects on the

491   amplitudes of seasonal displacement with no obvious long-term trend. Meanwhile, we clearly

492   see that these fluctuations (grey background in Figure 8a) are almost erased from the

493   GRACE-derived minus GLDAS/Noah vertical displacements, and the obvious continuous

494   uplift are presented in grey background of Figure 8b, which is mainly because the

495   contributions from groundwater depletion in the NCP. Contrasts between the seasonal

496   amplitudes, phases and trends fit of vertical displacement derived by GRACE after removing

497   GLDAS/Noah effects and the original ones. Please see the Table S4 in the supporting

498   information.

499

500   For the results described above, after the subtraction of the GLDAS/Noah contributions,

501   GRACE-derived heights largely reflect loading effects from the groundwater (natural and

502   anthropogenic factors) and anthropogenic contributions. The anthropogenic impact on mass

503   change was investigated by Tang et al. [2013] for the effect of inter-basin diversion, reservoir

504   and coal transport distribution on the GRACE-derived estimates of groundwater depletion in

505 the NCP. Results from their investigation showed that the trend of anthropogenic

506 contributions was equivalent to 4.83 mm/yr water thickness (described by equations in Table

507 2 of Tang et al. [2013]) during 2003~2011 for the whole NCP. This means that there was a

508 large groundwater depletion contribution for the GRACE-derived vertical displacements in

509 long-term uplift. Investigating groundwater withdrawal due to anthropogenic activities

510 (drinking water extraction, agricultural irrigation and industrial manufacturing) should be of

511 high importance because precipitation data for this area (shown in Figure 7) indicated no

512 long-term droughts during the GRACE observation period of 2003~2011.

513

514 **5. Discussion**

515 **5.1 The Loading Effects of Non-tidal Ocean and Atmospheric Variations**

516 As part of the processing performed by the GRACE Project, the GRACE Stokes coefficients

517 (denoted by the GRACE Project as ''GSM'' coefficients) have had modeled estimates of the

518 atmospheric and oceanic mass signals removed. Thus the GRACE coefficients include the full

519 effects of terrestrial water storage. The GRACE Project provides the modeled atmospheric

520 and oceanic contributions to the Stokes coefficients in two forms: ''GAC'' files which include

521 the global atmospheric and oceanic effects, and ''GAD'' files which have had the atmospheric

522 signals over land set to zero. The coefficients in the GAD file therefore represent ocean

523 bottom pressure variations. ''GAA'' files are those add CSR's GAC files to the GSM files, and

524 subtract the GAD files. The coefficients in the GAA file represent atmospheric pressure

525 variations.

526

527   As is mentioned in Section 1, the cause of the difference between our results and Liu's work

528   [Liu et al., 2014] is we removed atmospheric and non-tidal ocean loading effects while they

529   did not. However, we found that the amplitude of GPS after removing atmospheric and

530   non-tidal ocean loading effects, is still greater than the GRACE while we added the AOD1B

531   (GAC solution) de-aliasing model to the GRACE solutions (i.e., no atmospheric and non-tidal

532   ocean corrected, please see the Table S1 in the supporting information). The most obvious

533   difference between our results and Liu's work [Liu et al., 2014] is that they adopt the load

534   Love numbers from Guo et al. [2004] to transform these coefficients into vertical surface

535   displacement estimates. We check the two results of Love numbers (ocean-load and

536   atmospheric pressure-load) from Guo et al. [2004], there are significant differences between

537   ocean-load and atmospheric pressure-load Love numbers. Meanwhile, we compared k_n Love

538   numbers from Guo et al. [2004] (Liu et al.'s work) and k_n Love numbers from Han and Wahr

539   [1995] (our work) with the k_n Love numbers used in ADO1B products [Farrell, 1972],

540   respectively. The different Love numbers have caused the amplitude of the same station from

541   Liu's GRACE-derived vertical displacements much more than GPS and our GRACE results,

542   due to k_n from atmospheric pressure-load Love numbers [Guo et al., 2004] significantly larger

543   than Love numbers from Han and Wahr [1995] and Farrell [1972]. The detailed analysis of

544   the different Love numbers from Guo et al. [2004], Han and Wahr [1995] and Farrell [1972],

545   please see the Section S1 in the supporting information. Moreover, Table S3 in the supporting

546   information indicate that our correlation results of IGS stations (BJFS, BJSH, JIXN, TAIN

547   and ZHNZ) are consistent with Liu's work [Liu et al., 2014], indicating that the seasonal

548   variations might come from the same geophysical process. The WRMS residual reduction

549 ratio for all the stations ranged from 19% to 85%, which is better than Liu's work [Liu et al.,

550 2014]. However, the correlation and WRMS reduction between GPS and GRACE are weak

551 when atmospheric and non-tidal ocean effects was removed, with the average correlation and

552 WRMS reduction reduce to 75.6% and 28.9%, respectively. This is mainly because the

553 seasonal hydrologic process is major contributors to seasonal changes, and different stations

554 are greatly influenced by the surrounding hydrological process.

555

556 **5.2 Removing Hydrological Loading Displacement from GPS Using GRACE Data**

557 Coordinate variations measured by GPS stations, principally for the vertical component, have

558 been used to investigate global [Dong et al., 2002] and local [Grapenthin et al., 2006] tectonic

559 activity, as well as seasonal displacement modes for constraining estimates of continental,

560 atmospheric and ocean water storage. Some previous studies [e.g., Fu et al., 2012] have

561 focused on the vertical component of crustal motion with relying on the accurate

562 interpretation of GPS motion in terms of surface stress or tectonic movement. Thus, the

563 displacement signal from surface mass loading is a source of noise [van Dam et al., 2007].

564 For these applications, they would like to obtain reliable loading models or even surface mass

565 observations, which can be used to reduce the environmental loading contributions to the GPS

566 observations. In this study, we also attempt to separate tectonic and hydrological effect using

567 GRACE-derived hydrological vertical rates. As mentioned in the Section 3, the good seasonal

568 correlation between GRACE and GPS signals indicates that the long-term uplifts revealed by

569 GRACE detections are probably true and mixed in the GPS measurements.

570

571   Figure 9 shows results for individual GPS time series. Crustal subsidence or uplift due to

572   vertical tectonic motion and TWS changes in the studied period are clearly evident in the

573   vertical component shown in most of the GPS stations; In fact, the analysis in the five IGS

574   GPS stations (BJFS, BJSH, JIXN, TAIN and ZHNZ) suggests that the GPS vertical time

575   series can be described by two different rates around 2010, due to a continuous decrease in

576   TWS from 2004 until 2009; towards the end of 2009 the rate of this decrease slowed and rate

577   started to rise since 2010 (please see Figure 6). Thus, we divided it into two sub-periods when

578   fitting GPS and GRACE trend for these five stations (Figure 9a). GPS trend changes indicate

579   an overall uplift for the whole region at the 0.04~1.47 mm/yr level from 2004 to 2009, but the

580   rate of change direction is inconsistent in different GPS stations at –0.94~2.55 mm/yr level

581   from 2010 to 2013 (Table 1).

582

583   In addition, the long-term trend rate is different in different areas from 2010 to 2013 (Figure

584   9b). For example, the trend rate from GPS measurements shows the uplift in western NCP

585   (Shanxi-SX,and some of Hebei-HE stations), but opposite trends in the central and eastern

586   plain of NCP (Beijing-BJ, Tianjin-TJ and some of Hebei-HE stations). The groundwater

587   depletion which occurs in the shallow unconfined aquifers in Piedmont Plain leads to the

588   loading uplift effect from mass loss. But groundwater depletion occurs in the deep confined

589   aquifers in the central and eastern plain of NCP, which causes serious ground subsidence,

590   rather than ground uplift caused by groundwater loss.

591

592   It is also possible that some GPS signals could be a result of loading from changes in the

593   distribution of water stored in the surface and ground around the GPS surrounding region. To

594   remove those contributions, Stokes coefficients output from the GRACE model were used to

595   compute crustal motion at the NCP (Figure 8a), and then transform the monthly results into

596   daily resolution data using a spline interpolation. In addition, GRACE solutions are corrected

597   for GIA while GPS ones are not. Here Stokes coefficients results from A et al. [2013] were

598   used to remove GIA effects from GPS measurements, which is about 0.2~0.4 mm/year in the

599   land areas of China and 0.28~0.33 mm/year in the NCP (Please see the Figure S5 and Table

600   S4 in the supporting information).

601

602   We compute the GRACE-derived long-term uplift for all continuous GPS sites used in this

603   paper. The results indicate an overall uplift for the NCP region. Then we remove this TWS

604   induced uplift from GPS actual observed vertical rates to derive the corrected vertical

605   velocities. Figure 10 divided the time into two sub-periods (2004~2009 and 2010~2013) to

606   indicate an overall long-term trend before (gray arrow) and after (red arrow) removing

607   hydrological loading displacement for the whole region. Secular displacement results between

608   2004 and 2009 show that loading displacement due to the TWS loss reduce the uplift rate of

609   GPS to some extent, and groundwater exploitation was the main contributor to crustal uplift

610   caused by TWS loss in the NCP (BJFS, BJSH and JIXN in the Figure 10a). However, studies

611   indicate that groundwater withdrawal produces localized subsidence which can be largely

612   relative to tectonic displacement [Bawden et al., 2001]. Therefore, in this study, more

613   attention was paid to land subsidence due to groundwater loss.

614

615   **5.3 Land subsidence in the central and eastern of NCP**

616   Land subsidence has been commonly observed in the NCP, and has become the main factor

617   that impacts regional sustainable economic and social development [Guo et al., 2015]. Over

618   the past years, the scope and magnitude of land subsidence has expanded. In this study, we

619   used GPS sites to obtain time series of land subsidence evolution characteristics. The trend

620   rates from GPS sites, after removing the rates from GRACE-derived long-term uplift and GIA

621   effects can be seen in Figure 10b (the gray background areas in the dashed white box) to

622   reflect the rate of land subsidence from 2010 to 2013, which is because the groundwater

623   exploitation in the deep confined aquifers has a more serious impact on land subsidence [Guo

624   et al., 2015]. The results show that Tianjin becomes the most serious subsidence area, e.g., in

625   the Tanggu and Hangu district (TJBH), with an average subsidence of ~14 mm/yr after 2010;

626   In Wuqing district (TJWQ), recent subsidence averaged ~43 mm/yr. Because the Cangxian

627   district (HECX) is close in proximity to the Jinghai region of Tijian, the sedimentation rate of

628   ~20 mm/yr can represent the subsidence trend of southwest Tianjin. However, the difference

629   of spatial distribution of land subsidence is large in Tianjin, and uneven settlement

630   characteristics are obvious. For example, the southwest and western areas of Tianjin are the

631   most serious areas, and the trend of land subsidence exists in the northward but the amplitude

632   is small relative to the southwest and western areas, i.e., (JIXN site shows a small negative

633   trend (~–0.6 mm/yr). The cause for subsidence in the Tianjin area is linked to over

634   exploitation of groundwater, an issue that has not been effectively controlled resulting in

635   rapidly developing land subsidence in the suburbs in recent years [Yi et al., 2011].

636

637   In the central and eastern region of NCP, where disastrous land subsidence has also occurred

638   in Beijing and cities in central of Hebei province and the northeast of Shandong province, for

639   instance, large subsidence zone in Hebei province has formed from north to south, where start

640   from the western region of Beijing (BJFS, BJSH and BJYQ station), via the eastern region of

641   Xingtai and Handan (HELY station), extend to the northern of Hebi (HAHB station belong to

642   Henan province).

643

644   However, results from our investigation show that the center of land subsidence does not

645   completely overlap the TWS loss contributions (see the secular trend maps of the TWS

646   changes of NCP in Figure 2). The uplift still exists even when we removed the rates from

647   GRACE-derived and GIA effects in the piedmont of Taihang Mountains and the western part

648   of NCP (Shanxi province), where the groundwater depletion occurs in the shallow unconfined

649   aquifers have not led to a large area of subsidence. The reason for this difference with the

650   western region of NCP is that crustal uplift is mainly controlled by tectonic movement, which

651   is the orogenic belt and plateau area in western of the Taihang Mountains basic in the uplift.

652   In our results, most of the corrected vertical velocities at GPS stations, especially in the

653   central and eastern region of NCP, agree with the previous study results, i.e., combining with

654   mobile and continuous GPS observation [Zhao et al., 2014] and using GPS stations from

655   GNSS and leveling data [MLR, 2015], The results of vertical crust movement in the NCP

656   from the previous study, please see the Figure S6 in the supporting information.

657

658   **6. Conclusions**

659   Temporal variations in the geographic distribution of surface mass (continental water, ocean

660   mass and atmospheric mass) can lead to displacement of the Earth's surface. Due to excessive

661   exploitation of groundwater resources the NCP area has become susceptible to land

662   subsidence, and it has become one of the most affected areas in the world. Calculating the

663   loading displacement can explain the natural displacement phenomenon, and it presents new

664   insight into the dynamics of land subsidence.

665

666   Traditional displacement observation has space limitations. Based on the elastic displacement

667   of the Earth's crust by surface loadings, this study combined GRACE and GPS data to

668   investigate vertical displacements in the NCP area. GRACE data was used to model vertical

669   displacements due to changes in hydrological loads. The results showed both GPS and

670   GRACE data to observe strong seasonal variations. Comparisons between the observed GPS

671   seasonal vertical displacement and GRACE-derived seasonal displacement demonstrated that

672   a consistent physical mechanism is responsible for TWS changes, i.e., the seasonal

673   hydrospheric mass movements due to climate variability cause periodic displacements of the

674   lithosphere.

675

676   As well as the significant seasonal characteristics, GRACE also exhibited a long-term mass

677   loss in this region; the rate of GRACE-derived TWS loss (after multiplying by the scaling

678   factor) in the NCP was 3.39 cm/yr from 2003 to 2009, which is equivalent to a volume of

679   12.42 km^3/yr. The rate was 2.57 cm/yr from 2003 to 2012, equivalent to a volume of 9.41

680   km^3/yr. The TWS loss was principally due to groundwater depletion in the NCP. We

681   calculated that the consequent trend rate caused by the load mass change using GRACE data

682   and removed this hydrological effect from observed GPS vertical rates. Secular displacement

683   results showed that TWS losses reduced loading displacement to some extent, but the trend

684   rates disagree due to the difference of spatial distribution with anthropogenic depletion of

685   TWS in the NCP.

686

687   Particularly, land subsidence has been affecting the central and eastern region of NCP,

688   especially in Tianjin for the past years. Over-pumping of groundwater is the main cause of

689   land subsidence which has led to comprehensive detrimental effects on the society, the

690   economy and the natural environment. The impact of groundwater exploitation in different

691   aquifer systems and active faults in the different regions on land subsidence needs to be

692   analyzed in future investigations. For example, using GRACE to remove mass loading signals

693   from a GPS record requires either confidence that there is no concentrated load signal very

694   near the site, or a scaling factor based on a reliable model of the mass change (the

695   groundwater depletion rate estimated from monitoring well stations) pattern around the site.

696

714

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878

879 **Table captions:**

880 **Table 1.** GPS Station information.

881

882 **Table 2.** Trends of GRACE-derived TWS and GWS (GRACE minus GLDAS/Noah), in situ

883 measurements (shallow aquifers) and compare with the previous studies during 2003–2012.

884

885 **Figure captions:**

886 **Figure 1.** Study region of North Plain China (NCP) showing locations of continuous GPS

887 stations. White dots represent continuous GPS sites in the Crustal Movement Observation

888 Network of China (CMONOC) and red stars represent the International GNSS Service (IGS)

889 sites). Cities and provinces are labeled as follows: Beijing (BJ), Tianjin (TJ), Hebei province

890 (HE), and Shanxi province (SX).

891

892 **Figure 2.** The 2003~2012 secular trend maps (cm/yr) of the terrestrial water storage (TWS)

893 changes in North Plain China (NCP) and surrounding regions derived from GRACE data.

894 Results have been destriped and smoothed with a 250-km Gaussian smoothing function.

895

896 **Figure 3.** Daily values of the vertical (positive upward) components of position, as measured

897 at IGS GPS sites BJFS, ZHNZ, BJSH, JIXN and TAIN. The example of displacement due to

898 atmospheric and non-tidal ocean loading at BJFS IGS sites are shown in (b).

899

900 **Figure 4.** Surface horizontal (north and east components) and vertical deformation modeled

901 by GRACE in four IGS sites. (a) and (b) show the time series and trend rates of north and east

902 components in BJFS, JIXN, TAIN and ZHNZ, respectively, (c) show the time series of

903 vertical displacements.

904

905 **Figure 5.** Time series showing daily values (a) and fitting results (b) of the vertical (positive

906 upward) components from GPS and GRACE-derived at five IGS GPS sites.

907

Figure 6. Comparison of annual amplitudes and initial phases between GPS (grey) and

GRACE (red). The initial phases are counterclockwise from the east (reference time is

2004.0).

911

Figure 7. Time series showing total terrestrial water storage (TWS) changes in the spatially

averaged area (kernel) of the NCP estimated from CSR GRACE data, monthly groundwater

level changes observed by monitoring wells after multiplying by mean value of specific yields

in the NCP during 2002~2012 and the daily precipitation data (rainfall amount) for weather

stations during the period of 2003~2012 from CMDSSS. The black dashed curve is the

temporal smoothing GRACE-based result, the red and blue dashed curve are the long trend of

GRACE-based result during 2003~2009 and 2003~2012, respectively.

919

Figure 8. GRACE-derived smoothed (dash curves) and long-term (solid curves) vertical

displacement time series due to load changes (a), the groundwater depletion contributions

estimated from GRACE minus GLDAS data for smoothed (dash curves) and long-term (solid

curves) vertical displacements (b), as measured at five IGS stations and twenty CMONOC

stations in NCP and its surrounding region. The grey background highlight part shows

inflexion effects due to TWS changes in the vertical component.

926

Figure 9. Smoothed (dash curves) and long-term (solid curves) versions of daily values of the

vertical (positive upward) component of position, as measured at twenty nine GPS sites in

929   NCP and its surrounding region, (a) five IGS stations and (b) twenty four CMONOC stations.

930

931   **Figure 10.** GPS (gray arrow, positive upward) and corrected GPS (red arrow, positive upward)

932   vertical trend rate after subtracting the GRACE-derived long-term uplift rate due to load

933   changes and GIA effect between 2004 and 2009 (a), and between 2010 and 2013 (b).

934

Table 1:

Stations	Lat.	Lon.	Time	Annual Amplitude of vertical displacement (mm)		Annual Phase of vertical displacement (days) Reference time is 2004.0		Trend Rates of vertical displacement (mm/yr) 2004~2009		Trend Rates of vertical displacement (mm/yr) 2010~2013	
				GPS	GRACE	GPS	GRACE	GPS	GRACE	GPS	GRACE
BJFS[*]	39.6	115.8		2.50 ±0.26	1.35 ±0.24	40.09 ±6.39	359.63 ±10.73	1.47 ±0.14	0.58 ±0.06	−0.37 ±0.23	0.26 ±0.13
BJSH[*]	40.2	116.2		3.25 ±0.23	1.25 ±0.23	52.75 ±4.20	1.00 ±11.09	0.12 ±0.12	0.53 ±0.06	−0.94 ±0.25	0.14 ±0.13
JIXN[*]	40	117.5	2003 ~2013	2.46 ±0.22	1.32 ±0.23	32.20 ±5.11	359.72 ±10.56	1.21 ±0.12	0.53 ±0.06	−0.19 ±0.20	0.09 ±0.13
TAIN[*]	36.2	117.1		3.31 ±0.32	2.07 ±0.39	16.44 ±5.66	349.43 ±11.36	0.18 ±0.15	0.80 ±0.09	0.46 ±0.31	0.04 ±0.16
ZHNZ[*]	34.5	113.1		2.38 ±0.36	2.24 ±0.43	28.18 ±8.94	354.76 ±11.39	0.04 ±0.15	0.65 ±0.10	2.55 ±0.32	−0.35 ±0.17
BJGB[#]	40.6	117.1		3.61 ±0.41	1.25 ±0.23	32.07 ±6.58	4.25 ±11.11		0.49 ±0.06	0.25 ±0.34	0.02 ±0.13
BJYQ[#]	40.3	115.9		3.55 ±0.41	1.23 ±0.23	25.82 ±6.87	3.34 ±11.26		0.52 ±0.06	−0.41 ±0.34	0.14 ±0.13
HAHB[#]	35.6	114.5		3.44 ±0.42	2.13 ±0.42	24.12 ±6.93	349.19 ±11.79		0.77 ±0.10	−0.55 ±0.27	−0.28 ±0.17
HAJY[#]	35.1	112.4		2.28 ±0.51	2.05 ±0.44	9.28 ±13.00	355.65 ±12.80		0.84 ±0.10	−0.30 ±0.33	−0.40 ±0.17
HECC[#]	40.8	115.8		2.49 ±0.39	1.17 ±0.23	9.25 ±9.05	11.15 ±11.81		0.49 ±0.06	1.32 ±0.25	0.06 ±0.13
HECD[#]	41	117.9		4.09 ±0.36	1.27 ±0.23	40.28 ±5.21	7.63 ±11.09		0.45 ±0.06	−0.68 ±0.25	−0.07 ±0.13
HECX[#]	38.4	116.9		4.57 ±0.51	1.62 ±0.29	41.20 ±6.82	348.56 ±10.80		0.73 ±0.07	−20.85 ±0.38	0.26 ±0.14
HELQ[#]	38.2	114.3		2.06 ±0.37	1.67 ±0.28	30.89 ±10.63	354.34 ±9.95		0.68 ±0.07	1.76 ±0.26	0.31 ±0.14
HELY[#]	37.3	114.7		2.65 ±0.37	1.88 ±0.33	10.54 ±8.44	350.61 ±10.56		0.79 ±0.08	0.30 ±0.27	0.11 ±0.15
HETS[#]	39.7	118.2		1.59 ±0.42	1.39 ±0.24	279.75 ±15.31	355.30 ±10.28		0.53 ±0.06	3.70 ±0.32	0.07 ±0.13
HEYY[#]	40.1	114.1		3.40 ±0.39	1.20 ±0.23	2.92 ±6.44	7.32 ±11.44		0.49 ±0.06	0.76 ±0.30	0.29 ±0.13
HEZJ[#]	40.8	114.9	2010 ~2013	1.95 ±0.35	1.13 ±0.23	364.91 ±10.74	15.62 ±12.11		0.47 ±0.06	1.06 ±0.25	0.11 ±0.13
NMTK[#]	40.2	111.2		3.37 ±0.47	1.02 ±0.23	8.85 ±7.09	25.83 ±13.67		0.37 ±0.06	1.20 ±0.37	0.51 ±0.13
NMZL[#]	42.2	115.9		1.72 ±0.39	1.15 ±0.23	37.43 ±14.85	30.16 ±12.06		0.41 ±0.06	−0.49 ±0.28	−0.10 ±0.13
SDJX[#]	35.4	116.3		2.36 ±0.40	2.22 ±0.41	39.05 ±9.97	350.76 ±11.00		0.71 ±0.10	0.78 ±0.33	−0.07 ±0.17
SDZB[#]	36.8	117.9		3.59 ±0.44	1.90 ±0.37	25.65 ±6.87	347.50 ±11.50		0.79 ±0.09	−1.12 ±0.30	0.12 ±0.16
SXCZ[#]	36.2	113.1		3.99 ±0.47	1.93 ±0.39	35.27 ±6.48	352.64 ±12.24		0.87 ±0.09	0.22 ±0.30	−0.22 ±0.16
SXGX[#]	36.2	111.9		1.17 ±0.51	1.81 ±0.39	311.44 ±26.46	359.06 ±12.86		0.92 ±0.09	3.17 ±0.38	−0.17 ±0.16
SXLF[#]	36	111.3		3.65 ±0.48	1.79 ±0.40	18.16 ±7.77	363.02 ±13.33		0.95 ±0.10	1.21 ±0.31	−0.19 ±0.17
SXLQ[#]	39.3	114		3.63 ±0.47	1.38 ±0.24	25.49 ±7.95	362.70 ±10.45		0.54 ±0.06	1.42 ±0.33	0.39 ±0.13
SXXX[#]	35.1	111.2		2.93 ±0.54	1.98 ±0.43	15.09 ±10.44	363.17 ±13.18		0.90 ±0.10	1.30 ±0.41	−0.36 ±0.17
TJBD[#]	39.6	117.3		3.36 ±0.48	1.38 ±0.24	25.80 ±7.38	355.65 ±10.54		0.58 ±0.06	−1.10 ±0.33	0.16 ±0.13
TJBH[#]	39	117.6		6.25 ±0.45	1.49 ±0.26	42.18 ±9.56	350.10 ±10.60		0.64 ±0.06	−16.84 ±0.37	0.20 ±0.13
TJWQ[#]	39.3	117.1		5.08 ±0.49	1.43 ±0.25	0.11 ±8.23	353.28 ±10.58		0.62 ±0.06	−44.46 ±0.45	0.21 ±0.13

937   [*]IGS sites: the observation time between 2003 and 2013.

938   [#]CMONOC sites: the observation time between 2010 and 2013.

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Table 2:
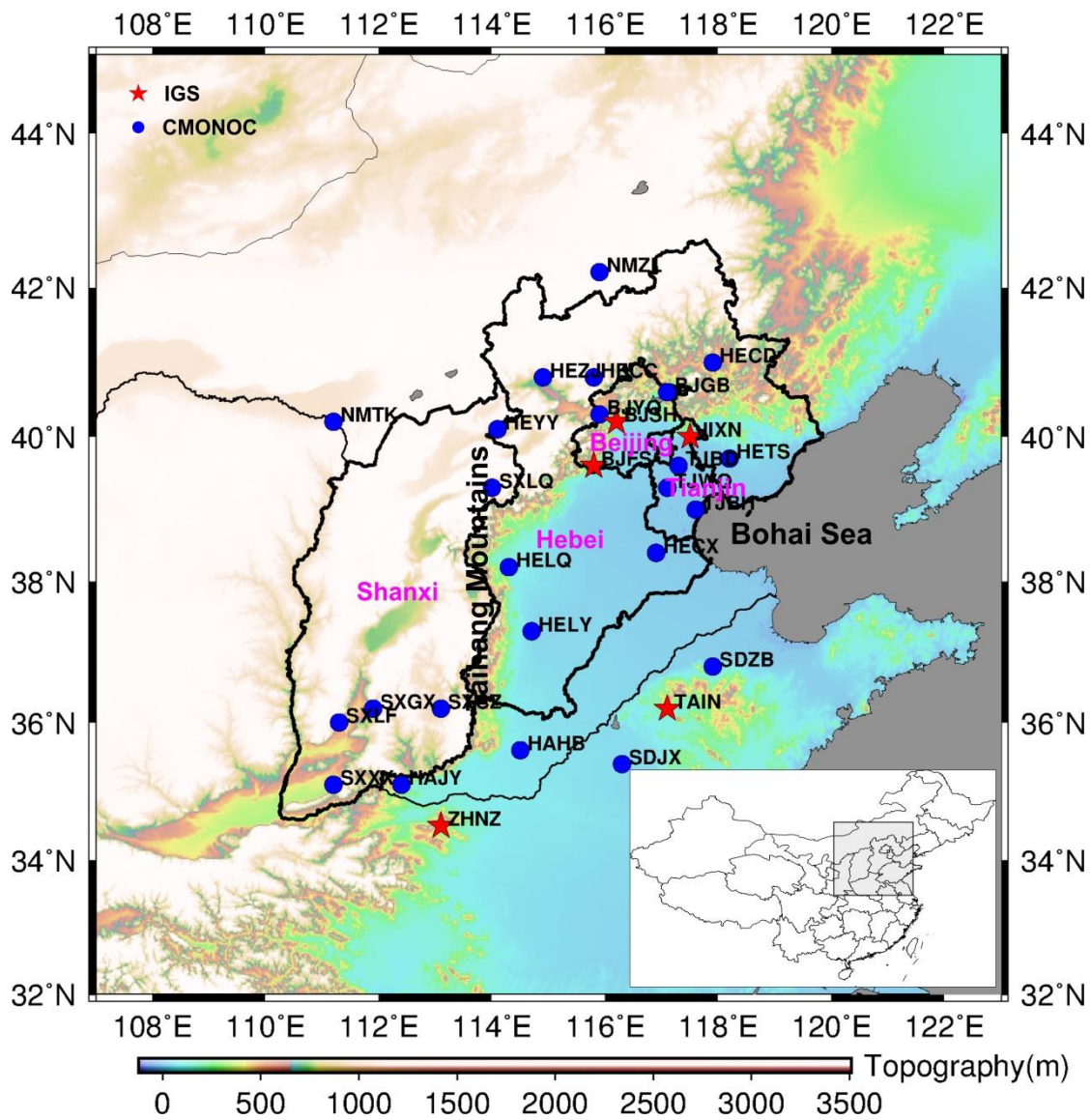
945

	TWS 2003~2009	TWS 2003~2012	GWS 2003~2009	GWS 2003~2012
[a]This sutdy	−1.62±0.39	−1.23±0.23	−1.17±0.41	−1.28±0.25
[a]This sutdy after multiplied by a scaling factor=1 (cm)/0.47 (cm)	−3.39±0.81	−2.57±0.49	−2.49±0.41	−2.72±0.25
[b]This sutdy after multiplied by a scaling factor=3.6626 (km^3)/0.47 (cm)	−12.42±3.15	−9.41±1.79	−9.12±3.34	−9.96±1.95
[a]In situ measurements (shallow aquifers)			−1.57±0.31	−0.98±0.20
[a]Huang et al. (2015)				−2.83±0.71
[a]Feng et al. (2013)			−2.2±0.3 (2003~2010)	
[a]Tang et al. (2013)				−0.8~−1.4 (2003~2011)
[a]Su et al. (2011)	−1.1 (2002~2010)		−0.5 (2002~2010)	
[a]Moiwo et al. (2009)	−1.68 (2002~2009)			
[a]Zhong et al. (2009)	−2.4 (2003~2007)			

946 [a] cm/yr of the water thickness

947 [b] km^3/yr of the mass

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949   **Figure 1:**

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Mass loading for displacements

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961   **Figure 5:**

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966   **Figure 7:**

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970   **Figure 8:**

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(a) GRACE-derived vertical displacement   (b) GRACE-derived minus GLDAS vertical displacement

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973   **Figure 9:**

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(a) GPS sites from the IGS

(b) GPS sites from the CMONOC

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976   **Figure 10:**

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