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   We employ twenty-nine continuous Global Positioning System (GPS) time series data

16   together with data from Gravity Recovery and Climate Experiment (GRACE) are analyzed to

17   determine the seasonal displacements of surface loadings in the NCP. Results show significant

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

19   displacement component; the average correlation and WRMS reduction between GPS and

20   GRACE are 75.6% and 28.9%, respectively, when atmospheric and non-tidal ocean effects

21   were removed, but the peak to peak annual amplitude of GPS (1.2~6.3 mm) is greater than

22   GRACE-derived (1.0~2.2 mm). We also calculate the trend rate as well as the seasonal signal

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23   caused by the mass load change from GRACE data, the rate of GRACE-derived Terrestrial

24   Water Storage (TWS) loss (after multiplying by the scaling factor) in the NCP was 3.39 cm/yr

25   (equivalent to 12.42 km^3/yr) from 2003 to 2009. For a 10-year time span (2003 to 2012), the

26   rate was 2.57 cm/yr (equivalent to 9.41 km^3/yr). Basing on spherical harmonic coefficients for

27   the gravity field and load Love numbers, we use GRACE model to remove the vertical rates

28   of elastic displacements due to the surface mass change from GPS data. An overall uplift for

29   the whole region at the 0.04–1.47 mm/yr level from 2004 to 2009, but the rate of change

30   direction is inconsistent in different GPS stations at -0.94–2.55 mm/yr level from 2010 to

31   2013.

32

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

34   the North China Plain

35

36   **1. Introduction**

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

38   or height component due to its large amplitude, has been used to study surface loading caused

39   by mass change. Site-position time series recorded by continuous GPS arrays have revealed

40   that vertical displacement variations can result from trend or seasonal distribution of mass in a

41   region or global changes that cause displacement of the Earth's surface (e.g., a change of

42   continental water [Bevis et al., 2005; van Dam et al., 2007; Wahr et al., 2013], ice [Sauber et

43   al., 2000; Khan et al., 2010; Nielsen et al., 2013], snow [Heki, 2001; Grapenthin et al., 2006],

44   ocean [van Dam et al., 2012; Wahr et al., 2014] and atmospheric mass [van Dam et al., 1994;

45   Boehm et al., 2007]).

46

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

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

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

50   that most significantly affects loading are large anthropogenic disturbances on groundwater

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

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

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

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

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

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

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

58   analysis of GRACE time-variable gravity field coefficients and GPS data [Kusche and

59   Schrama, 2005; van Dam et al., 2007; Fu and Freymueller, 2012; Fu et al., 2013]. In principle

60   the loading effects caused by the majority of mass redistributions near the Earth's surface are

61   from water, atmospheric, and ocean transports on daily to inter-annual timescales [Kusche and

62   Schrama, 2005]. The variations of the atmospheric and ocean contribution to the surface

63   displacement can be reasonably modeled, and therefore corrected, using global atmospheric

64   surface pressure data and space geodetic data, respectively. Thus, after removing the loading

65   effects of the atmospheric and ocean, GRACE-derived displacement and GPS data allow the

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

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

69   Variations in TWS may be related to precipitation, which is strongly driven by climate and

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

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

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

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

74   2003] and the Community Land Model (CLM) [Oleson et al., 2013]), surface water storage

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

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

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

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

79   2009] and dam construction for power generation and navigation [Wang et al., 2011]. These

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

81   All can cause variations in TWS can lead to the overall changes in crust displacement.

82

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

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

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

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

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

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

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89   groundwater depletion in the NCP [Feng et al., 2013; Moiwo et al., 2013; Tang et al., 2013;

90   Huang et al., 2015]. Liu et al. [2014] has discussed loading displacement in the NCP before.

91   Only five GPS stations (i.e., BJFS, BJSH, JIXN, TAIN, and ZHNZ) data are used in their

92   work. Although they calculated the seasonal amplitudes, phases and trends of vertical

93   displacement from GRACE and GPS, the atmospheric and non-tidal ocean loading effects

94   were not removed in the Liu et al.'s work, i.e., added the Atmosphere and Ocean De-aliasing

95   Level-1B (AOD1B) solution (GAC solution) back to the GRACE spherical harmonic

96   solutions.

97

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

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

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

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

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

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

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

105

106   **2. Data Analysis**

107   **2.1 GRACE Data**

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

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

110   2002 [Tapley et al., 2004a]. The Level-2 gravity products consist of complete sets of spherical

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

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

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

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

115   2005]. In this analysis, we assume that the gravitational and geometrical response of the Earth

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

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

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

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

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

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

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

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

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

125

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

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

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

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

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

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

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

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

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

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

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

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

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

139   information for details.

140

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

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

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

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

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

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

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

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

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

150   coefficients results from A et al. [2013] were used to remove contributions from Glacial

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

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

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

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

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

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

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

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

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

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

161 GRACE-derived TWS loss in the whole of the NCP [Feng et al., 2013; Moiwo et al., 2013] or

162 in different sub-regions of the NCP [Tang et al., 2013; Huang et al., 2015]. These

163 investigations, however, did not focus on regional displacement due to seasonal or long term

164 variations of hydrologic loading.

165

166 **2.2 GPS Data**

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

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

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

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

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

172 2013, which is consistent with GRACE time span. The 24 GPS sites of CMONOC provided

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

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

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

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

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

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

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

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

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

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

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

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

185

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

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

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

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

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

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

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

193   maintain consistency with the GIA effects present in the GRACE solutions, we remove GIA

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

195   [2013], which used the ICE5G ice history and VM2 viscosity profile [Peltier et al., 2004].

196

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

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

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

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

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

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

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

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

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

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

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

208   displacements at 2.5° ×2.5° spacing, http://geophy.uni.lu/ncep-loading.html, 2010). These

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

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

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

212   non-tidal ocean effects and its spatial resolution is 1°×0.3-1.0°, i.e., 1 degree longitude (zonal)

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

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

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

216

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

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

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

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

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

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

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

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

225   corrected atmospheric and non-tidal ocean, are summarized in Table S1 in the supporting

226   information.

227

228   **2.3 Elastic Displacements Due to Mass Loads**

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

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

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

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

233   of mass is:

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

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

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

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

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

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

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

241

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

243 equations:

244
$$\Delta n = dr(\theta, \phi) = -R \sum_{l=1}^{N_{max}} \sum_{m=0}^{l} \frac{\partial}{\partial \theta} \widetilde{P}_{l,m}(\cos \theta) \cdot (C_{lm} \cos(m\phi) + S_{lm} \sin(m\phi)) \frac{l_l}{1+k_l} , \qquad (2)$$

245
$$\Delta e = dr(\theta, \phi) = \frac{R}{\sin \theta} \sum_{l=1}^{N_{max}} \sum_{m=0}^{l} \widetilde{P}_{l,m}(\cos \theta) \cdot m(-C_{lm} \sin(m\phi) + S_{lm} \cos(m\phi)) \frac{l_l}{1+k_l} , \qquad (3)$$

246 where Δn and Δe are north and east components of the displacement, respectively, with both

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

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

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

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

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

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

253

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

271   [2013].

272

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

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

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

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

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

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

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

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

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

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

283   NCP.

284

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

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

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

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

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

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

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

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

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

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

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

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

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

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

299   amplitude) and largely pumped for agricultural usage in late spring months cause mass loads

300   decrease (the maximum positive of vertical amplitude). We observe the fact that the amplitude

301   of GPS is relatively larger than that of GRACE, it is not only exists in the IGS stations, but in

302   almost all stations except SXGX (Table 1). This indicates that GPS has a strong sensitivity for

303   local surface loading. By contrast, because the spatial resolution of GRACE data is limited to

304   approximately 300 km (N_{max}=60), GRACE-derived results are mainly constrained by large

305   scale areas. This means that GRACE-derived vertical displacements show a small difference

306   between stations due to the results are averaged over scales of several hundred km or more.

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308   As is mentioned above, the cause of the difference between our results and Liu's work [Liu et

309   al., 2014] is we removed atmospheric and non-tidal ocean loading effects while they did not.

310   However, we found that the amplitude of GPS after removed atmospheric and non-tidal ocean

311   loading effects, is still greater than the GRACE while we added the AOD1B de-aliasing

312   model to the GRACE solutions (i.e., no atmospheric and non-tidal ocean corrected, please see

313   the Table S1 in the supporting information). The most obvious difference between our results

314   and Liu's work [Liu et al., 2014] is that they adopt the load Love numbers from Guo et al.

315   [2004] to transform these coefficients into vertical surface displacement estimates. We check

316   the two results of Love numbers (ocean-load and atmospheric pressure-load) from Guo et al.

317   [2004], there are significant differences between ocean-load and atmospheric pressure-load

318   Love numbers. Meanwhile, we compared k_n Love numbers from Guo et al. [2004] (Liu et al.'s

319   work) and k_n Love numbers from Han and Wahr [1995] (our work) with the k_n Love numbers

320   used in ADO1B products [Farrell, 1972], respectively. The different Love numbers have

321   caused the amplitude of the same station from Liu's GRACE-derived vertical displacements

322   much more than GPS and our GRACE results, due to k_n from atmospheric pressure-load Love

323   numbers [Guo et al., 2004] significantly larger than Love numbers from Han and Wahr [1995]

324   and Farrell [1972]. The detailed analysis of the different Love numbers from Guo et al. [2004],

325   Han and Wahr [1995] and Farrell [1972], please see the Section S1 in the supporting

326   information

327

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

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

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

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

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

333   GPS heights. Because GRACE solutions truncate to l_{max}=60 and the Gaussian filtering was

334   used to lead to so smooth out concentrated loads. The phases of the GRACE data show that

335   the annual signal peaks (summer monsoon) basic between September and October and

336   indicate that the maximum load occurs in this two months. But there are several sites where

337   the GRACE signals disagree in phase with GPS data, which the annual signal peaks sometime

338   between August and September. The five signals of sites in the northwest foothills region of

339   NCP agree in phase, while annual amplitudes from GRACE are significantly less than GPS,

340   e.g., NMTK, NMZL, HEYY, HEZJ and HECC. The cause of mostly phase inconsistency may

341   be the different spatial resolution of GRACE compared to GPS. That is, GPS measurements

342   can sense the difference between loads very near the site, and loads a bit further away, but

343   GRACE with wavelengths on the order of 300 km reflects this variation at a monthly scale.

344   Another important reason is that a one-month sampling of GRACE means a phase sampling

345   of 30°, while a one-day sampling of GPS means a phase sampling of ~1°, the different

346   temporal sampling rate caused the inconsistent phase between GRACE and GPS.

347

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

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

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

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

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

353   displacement from GPS observed detrended height time series, please see the Table S4 in the

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

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

356   correlation results of IGS stations (BJFS, BJSH, JIXN, TAIN and ZHNZ) are consistent with

357   Liu's work [Liu et al., 2014], indicating that the seasonal variations might come from the

358   same geophysical process. The WRMS residual reduction ratio for all the stations ranged

359   from 19% to 85%, which is better than Liu's work [Liu et al., 2014]. However, the correlation

360   and WRMS reduction between GPS and GRACE are weak when atmospheric and non-tidal

361   ocean effects was removed, with the average correlation and WRMS reduction reduce to 75.6%

362   and 28.9%, respectively. This is mainly because the seasonal hydrologic process is major

363   contributors to seasonal changes, and different stations are greatly influenced by the

364   surrounding hydrological process. By contrast, the seasonal amplitudes and phases from

365   GRACE results are much more spatially coherent than those determined from the GPS

366   heights, caused by the different spatial resolution between them. In addition, we also attempt

367   to calculate GRACE-derived horizontal displacement using equation (2) and (3), and compare

368   it with the GPS measurements. An example (five IGS sites) of the comparison between

369   GRACE-derived and GPS observed horizontal displacements were presented to demonstrate

370   the correlation of seasonal horizontal variation caused by surface hydrological load. Please

371   see the Figure S4 in the supporting information.

372

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

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374   To estimate TWS changes averaged over the NCP, an averaging kernel based on weighted

375   Gaussian convolution to construct monthly time series from GRACE Stokes coefficients

376   described by equation (5) of Wahr et al. [2014] was used. This method extends the averaging

377   kernel convolution approach [Swenson and Wahr, 2002] by allowing for nonuniform

378   weighting during the convolution. We took the NCP "basin function" from the China

379   provincial boundary grid points and we convolved with a 250 km Gaussian smoothing. We

380   then applied this averaging kernel to GRACE Stokes coefficients to obtain a TWS time series

381   for NCP (Figure 7). The results identified a continuous decrease in TWS from 2004 to 2009;

382   the rate of this decrease slowed towards the end of 2009. The rate of TWS loss obtained by

383   this analysis was 1.62 cm/yr from 2003 to 2009 and 1.23 cm/yr from 2003 to 2012 (Table 2).

384

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

403

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

420   2013], which can be modeled using land surface model output such as those provided by the

421   GLDAS [Rodell et al., 2004]. We clearly see that these fluctuations are almost erased by

422   removing the modeled soil moisture (SM) of GLDAS/Noah, and the obvious uplift are

423   presented in the decomposition of the signal (Figure 8b), which is mainly because the

424   contributions from groundwater depletion in the NCP (please see the section 5.1 for discuss in

425   details).

426

427   **5. Discussion**

428   **5.1 Groundwater Depletion Contributions to Long-Term Uplift**

429   The GRACE-derived vertical displacements are also the effect of mass loading sensitive to

430   water at all depths: surface water storage, soil moisture, snow and groundwater, including

431   anthropogenic effects (i.e., groundwater withdrawal, inter-basin diversion, reservoir and coal

432   transport). To isolate the groundwater contributions, the Noah version of GLDAS which

433   possesses monthly intervals and spatial resolution of 1.0 degrees [Rodell et al., 2004] was

434   used to subtract monthly water storage estimates predicted by land surface models. GLDAS

435   generates a series of land surface forcing (e.g., precipitation, surface meteorology and

436   radiation), state (e.g., soil moisture and temperature, and snow), and flux (e.g., evaporation

437   and sensible heat flux) data simulated by land surface models. The GLDAS/Noah model can

438   provide values of snow, vegetation and all soil moisture layers, but it does not include

439   anthropogenic and climate-driven groundwater depletion. So groundwater contributions

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440   retained in heights time series when GRACE-derived vertical displacements subtracting

441   GLDAS/Noah effects.

442

443   Figure 8b shows the GRACE-derived height amplitudes after using output from the

444   GLDAS/Noah hydrology model to remove the continental water storage signal. The

445   calculated results show that the contributions of other types of TWS effects (except

446   groundwater) on the surface are small relative to groundwater depletion, and those loads

447   mainly effects on the amplitudes of seasonal displacement with no obvious long-term trend.

448   Compare the seasonal amplitudes, phases and trend fit of vertical displacements between

449   before and after remove GLDAS/Noah effects from GRACE-derived displacement, please see

450   the Table S4 in the supporting information.

451

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

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

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

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

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

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

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

459   2 of Tang et al. [2013]) during 2003-2011 for the whole NCP. This means that there was a

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

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

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

463   high importance because precipitation data for this area (provided by the China

464   Meteorological Data Sharing Service System, available at http://cdc.nmic.cn/home.do)

465   indicated no long-term droughts during the GRACE observation period of 2003-2011.

466

467   **5.2 Removing Hydrological Loading Displacement from GPS Using GRACE Data**

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

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

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

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

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

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

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

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

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

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

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

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

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

481

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

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

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

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

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

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

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

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

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

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

492   from 2010 to 2013 (Table 1).

493

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

495   9b). For example, the trend rate from GPS measurements shows the uplift in western NCP

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

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

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

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

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

501   rather than ground uplift caused by groundwater loss.

502

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

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

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

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

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

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

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

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

511   S4 in the supporting information).

512

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

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

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

516   velocities. Figure 10 divided the time into two periods (2004–2009 and 2010–2013) to

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

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

519   2004 and 2009 show that loading displacement due to the TWS loss reduce the uplift rate of

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

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

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

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

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

525

526   **5.3 Land subsidence in the central and eastern of NCP**

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

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

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

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

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

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

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

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

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

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

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

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

539   ~20 mm/yr can represent the subsidence trend of southwest Tianjin. However, the difference

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

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

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

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

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

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

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

547

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

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

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

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

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

553   Henan province).

554

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

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

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

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

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

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

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

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

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

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

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

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

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

568

569   **6. Conclusions**

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

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

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

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

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

575 insight into the dynamics of land subsidence.

576

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

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

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

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

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

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

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

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

585 lithosphere.

586

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

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

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

590 12.42 km^3/yr. The rate was 2.57 cm/yr from 2003 to 2012, equivalent to a volume of 9.41

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

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

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

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

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

596   TWS in the NCP.

597

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

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

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

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

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

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

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

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

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

607

624

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783 **Table captions:**

784 **Table 1.** GPS Station information.

785

786 **Table 2.** Trends of TWS derived by GRACE and scaled GRACE during 2003–2009 and

787 2003–2012.

788

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789 **Figure captions:**

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

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

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

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

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

795

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

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

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

799

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

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

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

803

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

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

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

807 vertical displacements.

808

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

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

811

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

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

814 2004.0).

815

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

817 averaged area (kernel) of the NCP estimated from CSR GRACE data. The dashed curve is the

818 temporal smoothing result.

819

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

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

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

823 curves) vertical displacements (b), as measured at 25 GPS sites in NCP and its surrounding

824 region. The grey background highlight part shows inflexion effects due to TWS changes in

825 the vertical component.

826

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

828 vertical (positive upward) component of position, as measured at 29 GPS sites in NCP and its

829 surrounding region, (a) 5 IGS stations and (b) 24 CMONOC stations.

830

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

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

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

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835   **Table 1:**

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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	2003 ~2013	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		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

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

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

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844   **Table 2:**

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| Time Span	GRACE Trend (cm/yr of the water thickness)	GRACE Scaled (×1/0.47) Trend (cm/yr of the water thickness)	GRACE Scaled (×3.6626/0.47) Trend (km^3/yr of the mass)
2003~2009	-1.62±0.39	-3.39±0.81	-12.42±3.15
2003~2012	-1.23±0.23	-2.57±0.49	-9.41±1.79

846

847 **Figure 1:**

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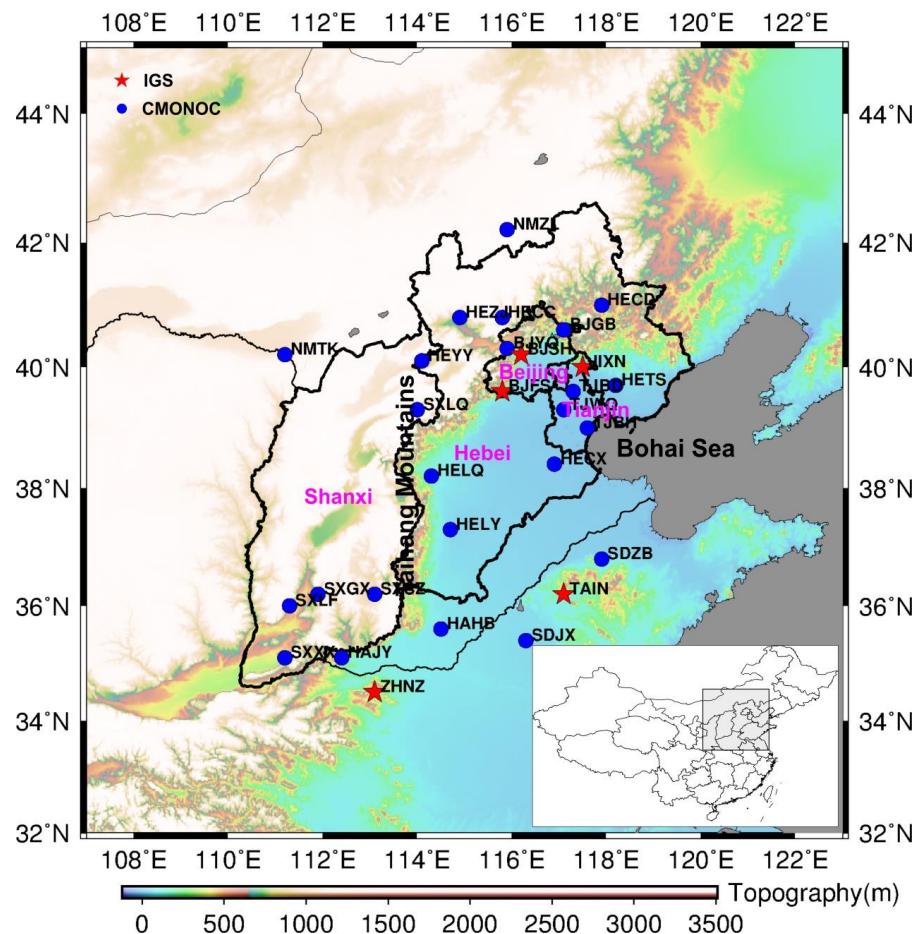
849

850   **Figure 2:**

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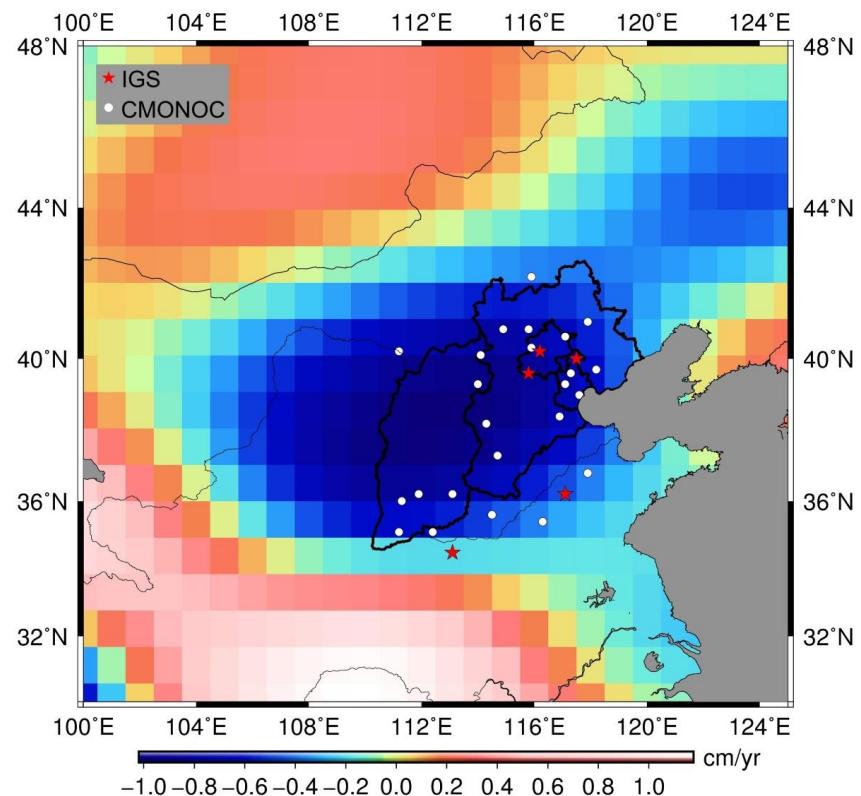
852

853   **Figure 3:**

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856   **Figure 4:**

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Mass loading for displacements
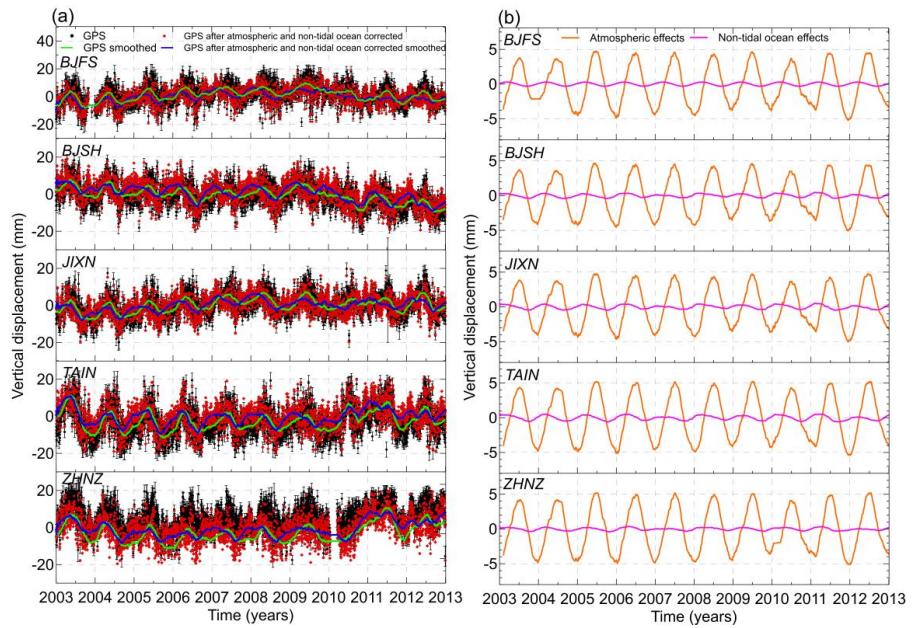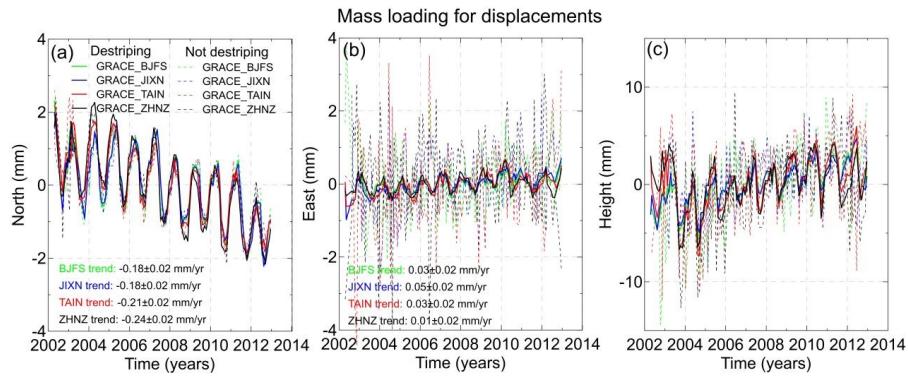
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859   **Figure 5:**
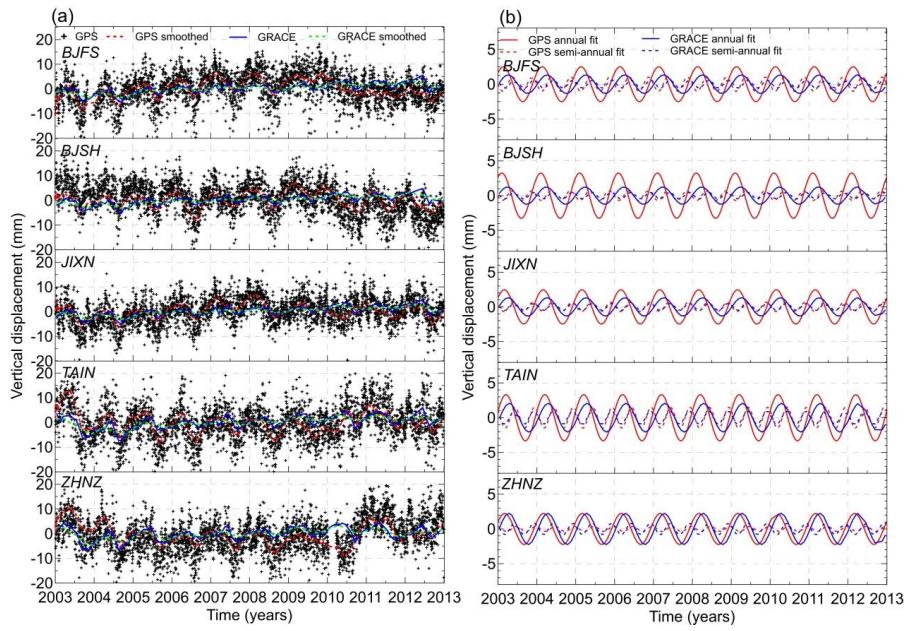
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861 **Figure 6:**

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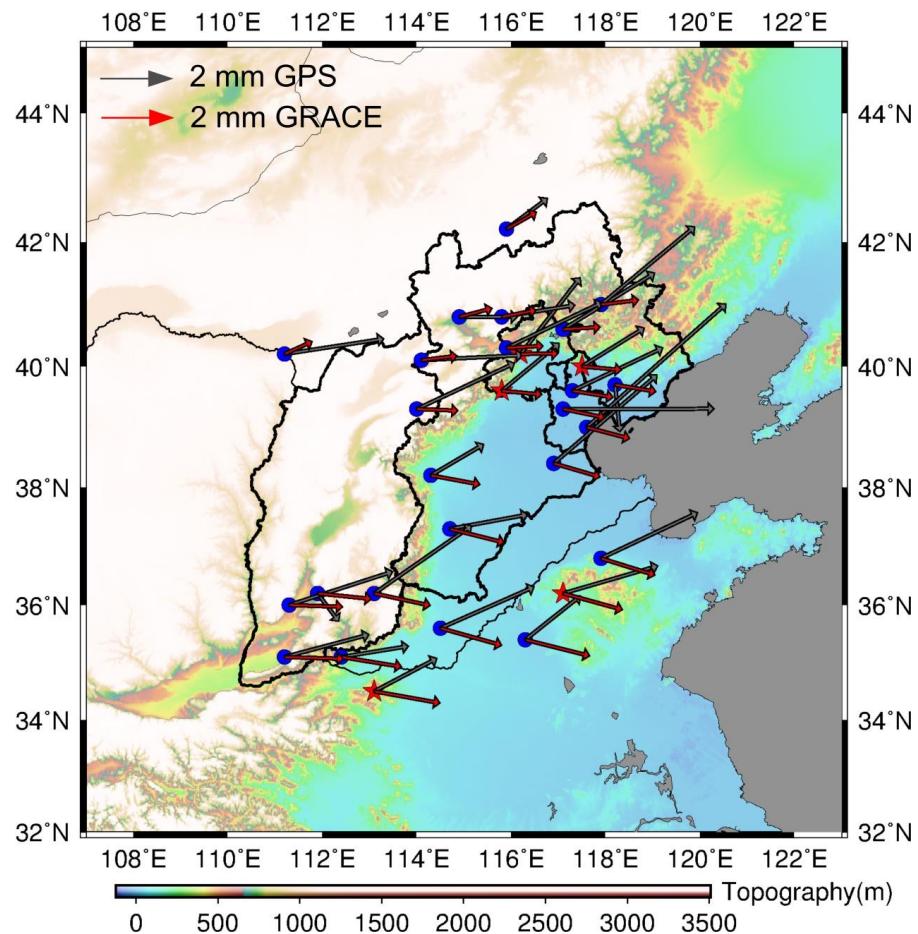

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864   **Figure 7:**

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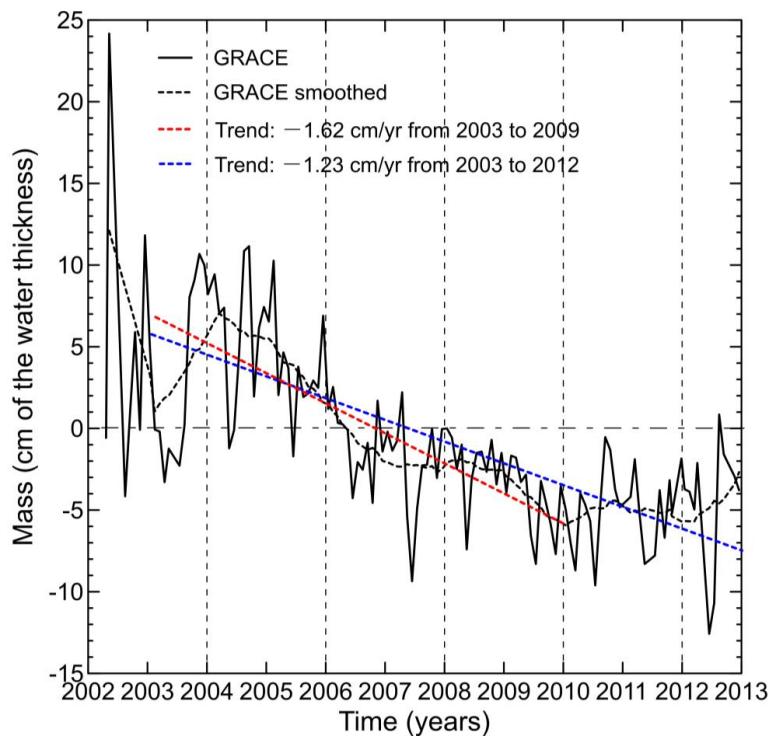
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868 **Figure 8:**

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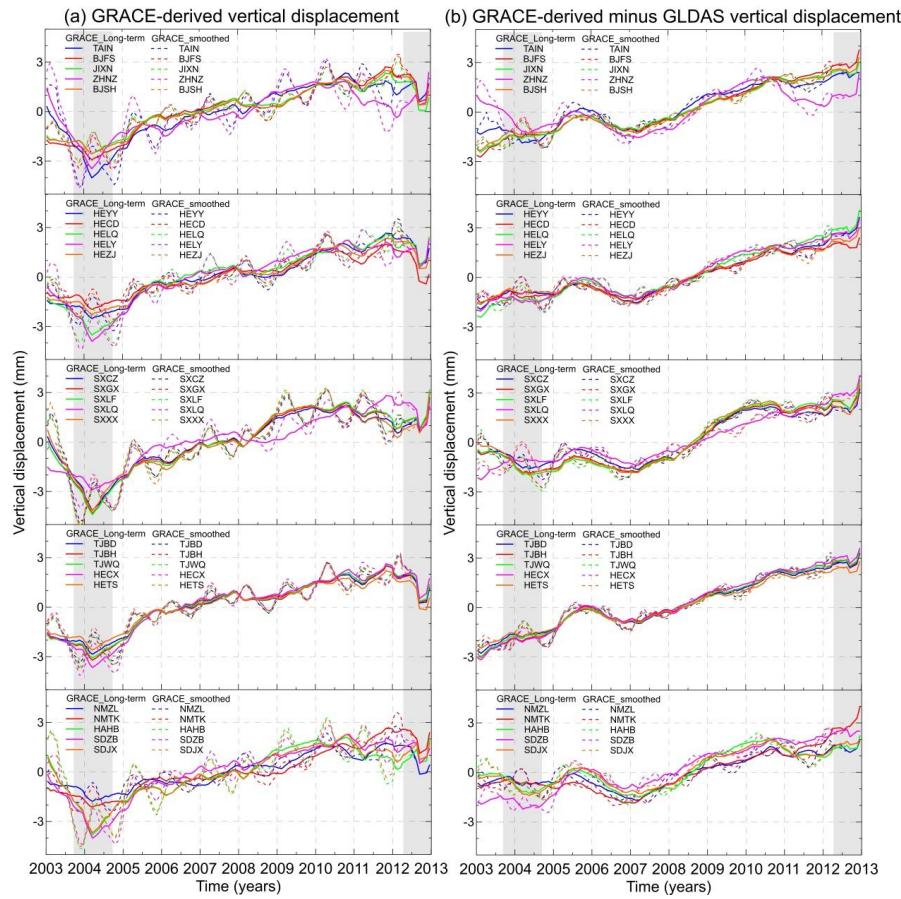
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871   **Figure 9:**

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874   **Figure 10:**

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