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Research Article

Effects and Correction of Atmospheric Pressure Loading Deformation on GNSS Reference Stations in Mainland China

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Atmospheric pressure loading (APL) deformation is one component of nontectonic deformation for Global Navigation Satellite System (GNSS) time series and is a kind of deformation response caused by a redistribution of atmospheric pressure. In this paper, we present an atmospheric data processing strategy to compute the APL based on a spherical harmonic expansion of the global atmosphere pressure changes. We also provide a sample model to describe the relativity between the global atmosphere pressure changes and APL vertical deformation. The results show that the variation of air mass has a major impact on the north-eastern area of East China, the eastern area of North China, and Northeast China, and the vertical crustal displacement caused by the atmosphere changes in these regions can reach about 20 mm. The correction of APL for vertical time series of GNSS reference stations in different regions indicates that the arid area of the Northwest China, Northeast China, Central China, and North China are greatly affected by APL. While for the station located in Sichuan-Yunnan region, the amplitude and period change are small after correction of APL for vertical time series of GNSS reference stations, which reveals that the area is seriously affected by tectonic movement and water migration loading. The correlation between atmospheric pressure changes and crustal deformation is analyzed, which shows that APL has a serious impact on the north-eastern area of North China, the Northeast China, and the eastern area of Central China when the variations in atmospheric pressure in mainland China are the same. The research results of this paper will provide some reference value for the study of crustal structural deformation and the establishment of geodetic datum.

1. Introduction

Atmospheric pressure loading is the elastic response of the earth caused by the redistribution of atmospheric pressure. Atmospheric pressure on the earth's surface changes within the range of 2–5 kPa due to environmental impact such as the gravity changes of the sun and moon and the changes in atmospheric pressure from weather changes [1–3]. The vertical displacement, horizontal displacement, and gravity changes of the earth's surface caused by global pressure changes can be up to ±2.5 cm, ±0.25 cm, and ±20 μGal [4, 5]. Therefore, it is of vital importance to deduct the influence of APL for the study of crustal tectonic movement, and the establishment of the geodetic reference frame and other similar hot issues in Earth Science.

One of the calculation methods for the APL is mainly based on the integration of Green's function [6, 7], the spherical harmonic function expansion [8, 9], and their model and arithmetic improvement [10, 11], combining with Love number of deformation characteristics of the earth surface by the earth model. Based on these calculation theory, Zhang et al. [12] assessed vertical crustal displacement of the Earth's crust in China caused by atmospheric loading effects, and the result showed that the vertical crustal displacement range can be up to 20~30 mm, predominantly at the seasonal time scale. Dach et al. [13] used three different methods to estimate the APL effect, compared with the solution without using APL to correct the repeatability of station coordinates increases by 20% when the APL effect is directly applied on the data processing and by 10% when the postprocessing APL correction is applied to the IGS weekly solution. Another method to take the effect of APL into account is to apply the effect directly on the data analysis at the observation level. Böhm et al. [14] had determined the geophysical APL correction model, and on the basis of the model, the APL corrections have been carried out on the observations obtained from space geodesy. Tregoning et al. [15, 16] and Dach et al. [13] hold the view that using this method is better than applying a postprocessing correction to the resulting coordinates. However, some important issues still remain to be resolved.

In this paper, we focus on APL in mainland China. Several studies have successfully assessed APL for space-geodetic techniques, but most of the studies were carried out with ocean tide loading, snow and soil moisture mass loading, and nontidal ocean mass loading [17–20]. However, the works of mainly studying atmospheric pressure loading deformation in detail is relatively few in mainland China [21, 22]. Luo and Sun [21] used the statistical technique and atmosphere pressure recorded in China and its adjacent region to establish a model for the precision estimation of the gravity and deformation variation caused by barometric pressure loading by using Green's function method. Wang et al. [23] studied the APL of the Three Gorge Region in China, and the results show that the impact of APL on the vertical deformation in the spatial distribution is mainly on the long wave, and the amplitude of annual variation is greater than 20 mm in this area.

In this article, we studied the APL deformation magnitude in different regions of mainland China and analyzed the APL influence on the vertical time series of GNSS reference stations in different region based on the spherical harmonics expansion, and we also studied the correlation between atmospheric pressure changes and vertical displacement of GNSS stations. The data used include GNSS reference stations and global atmospheric pressure reanalysis ERA-Interim by European Centre for Medium-Range Weather Forecast (ECMWF). The time resolution of atmospheric data is one day, and the spatial resolution is $0.5^{\circ} \times 0.5^{\circ}$. Bad data of the global atmospheric pressure is purged by a grid low-pass filtering.

2. Data Processing and Method

2.1. GNSS Solution. The GNSS data used in this paper come from the Crustal Movement Observation Network of China, which consists of continuously operating reference stations (255 stations) and regular operating reference stations (1974 stations). The data time span is from January 2010 to June 2016. We used the GAMIT/GLOBK software developed by the Massachusetts Institute of Technology and the Scripps Institute of Oceanography to solve GNSS data.

The GNSS data processing consists of three steps. Firstly, the GNSS stations are partitioned by using the method of a spatial division. Secondly, the orbital relaxation model, ionosphere-free combination, the solid tide correction model for IERS03, and the optimal troposphere and ionosphere correction model are used to solve the single-day orbital relaxation solution. Thirdly, taking into account the influence of abnormal single-day solutions, the coordinates of all stations are estimated by using GLOBK software and the IGS reference stations in and around China. In the adjustment, the GNSS station may be affected by the external conditions in the process of long time observation, such as coseismic and postseismic dislocation, strong solar magnetic storm and antenna replacement, and the single-day solution with large jump will be emerged. Therefore, it is necessary to correct or eliminate the abnormal single-day relaxation solution by analyzing the orderliness of time series, and the criterion of 3RMS and Inter-Quartile Range are used to eliminate outlier in this paper. With this method, we can finally get the accurate coordinates in ITRF2008 and available time series of east, north, and vertical (E N U) for GNSS stations.

2.2. Calculation Method of Atmospheric Pressure Loading. The atmospheric pressure loading deformation is basically caused by the change of the environmental quality of the earth's surface. The crustal deformation caused by the change of air mass can be regarded as the same mass of water, so we can convert daily atmospheric pressure to equivalent water height based on the transformation relation: "1 pa corresponds 0.10197 mm." The changes of environmental load of the earth's surface caused by changes in atmospheric pressure can be expressed by the equivalent water height difference relative to the reference time equivalent water height.

In the study, the value of average equivalent water height of all days in 2012 was taken as the reference value. So, it is common to expand the equivalent water height variation $\Delta h(\varphi, \lambda)$ as a sum of spherical harmonics [6, 24]:

$$\Delta h(\varphi, \lambda) = R \sum_{n=1}^{N} \sum_{m=0}^{n} \left[\Delta C_{nm}^{q} \cos m\lambda + \Delta S_{nm}^{q} \sin m\lambda\right] \overline{P}_{nm}(\sin \varphi), \tag{1}$$

where R is the radius of earth, ΔC_{nm}^{q} and ΔS_{nm}^{q} are dimensionless coefficients, n and m are the degree and order for the expansion of spherical harmonic coefficients, φ and λ are colatitude and east longitude. Since the spatial resolution of the global atmospheric pressure data used is 0.5 degrees, the degree and order can be generally expanded to 360 when the loading deformation is calculated.

The $\overline{P}_{nm}$ is the fully normalized associated Legendre functions:

$$\overline{P}_{nm}(\sin \varphi) = \sqrt{2(n+1)\frac{(n-m)!}{(n+m)!}} P_{nm}(\sin \varphi). \tag{2}$$

After obtaining the coefficients of the spherical harmonic expansion for the equivalent water height variation, the ground gravity change, and vertical and horizontal deformation of the ground station can be calculated according to the theory of earth loading deformation and gravity fields by the following equations [25, 26]:

$$\begin{aligned}
g(\varphi,\lambda) &= -3\frac{\rho_w}{\rho_e}\frac{GM}{R^2}\sum_{n=1}^{N}\frac{n+2h'_n-(n+1)k'_n}{2n+1}\sum_{m=0}^{n}\left[\Delta C^q_{nm}\cos m\lambda+\Delta S^q_{nm}\sin m\lambda\right]\overline{P}_{nm}(\sin\varphi),\\
\Delta u(\varphi,\lambda) &= 3\frac{\rho_w}{\rho_e}\frac{GM}{\gamma R}\sum_{n=1}^{N}\frac{h'_n}{2n+1}\sum_{m=0}^{n}\left[\Delta C^q_{nm}\cos m\lambda+\Delta S^q_{nm}\sin m\lambda\right]\overline{P}_{nm}(\sin\varphi),\\
\Delta e(\varphi,\lambda) &= 3\frac{k'_n\rho_w}{\sin(\varphi)\rho_e}\frac{GM}{\gamma R}\sum_{n=1}^{N}\frac{l'_n}{2n+1}\sum_{m=0}^{n}\left[\Delta C^q_{nm}\cos m\lambda+\Delta S^q_{nm}\sin m\lambda\right]\frac{\partial}{\partial\lambda}\overline{P}_{nm}(\sin\varphi),\\
\Delta n(\varphi,\lambda) &= -3\frac{k'_n\rho_w}{\rho_e}\frac{GM}{\gamma R}\sum_{n=1}^{N}\frac{l'_n}{2n+1}\sum_{m=0}^{n}\left[\Delta C^q_{nm}\cos m\lambda+\Delta S^q_{nm}\sin m\lambda\right]\frac{\partial}{\partial\varphi}\overline{P}_{nm}(\sin\varphi),
\end{aligned}\tag{3}$$

where $g(\varphi,\lambda)$, $\Delta n(\varphi,\lambda)$, $\Delta e(\varphi,\lambda)$, and $\Delta u(\varphi,\lambda)$ are the ground gravity change, East-West loading displacement, North-South loading displacement, and vertical deformation of the ground, φ and λ are the colatitude and longitude of the calculated point, h'_n is the radial Love number, l'_n is the horizontal Love numbers and k'_n is the gravity Love number, ρ_w is the density of water, $\rho_e = 5.5\times10^3\ \mathrm{kg/m^3}$, is the average density of solid earth, γ is the average gravity at the surface, G is the gravitational constants, and M is the gross mass of the solid earth.

It is noteworthy that the response of the sea to the change of air pressure is different from that of the land and the response of the sea is more complex, and this phenomenon greatly affects the vertical crustal movement in coastal areas. There are two main methods to improve this effect: an inverted barometer model considering the static equilibrium conditions of seawater and a barometer model hypothesizing the ocean as a rigid body [8, 12]. In this research, an inverted barometer model is used to describe the response of the sea to the change of air pressure.

3. Atmospheric Loading Deformation Characteristic in Mainland China

As shown above, the variation of the daily atmospheric pressure is defined as the difference from the reference value, and the changes of atmospheric pressure is converted to equivalent water height. So, the loading deformation at the station shows negative value and positive value (see Figure 1) and vertical displacement is in range from maximum negative value to maximum positive value. In order to clearly show the characteristics of the APL deformation in horizontal direction, the picture only demonstrates continuously operating reference stations (255 stations). For the vertical APL, 255 continuously operating reference stations and 1974 regular operating reference stations are all used to generate the grid result and then develop the background color (see Figure 1).

For the overall analysis of the mainland China region, the APL correction is roughly between −12 and 14 mm for different time periods, and the total deformation of the APL at each GNSS reference station varies between 8~20 mm. As shown in Figure 1, the vertical displacement of APL is small in February to April and August to October of each year and is large in May to July and November to January of next year.

In addition, the most influenced areas of atmospheric loading are northern of East China (see Figure 2) and southeastern of North China, and the maximum amount of effect is about 20 mm in vertical direction. Followed by the Northeast China and North China, the value of the APL is between 15~18 mm. The deformation value of APL in South China also has a great influence, and the maximum is about 15 mm. The least influence of APL is located in the Tibetan Plateau and its surrounding area, and the loading deformation value is about 9 mm. Wang et al. [17] found that the maximum deformation value of APL appeared in Northeast China, followed by North China. This conclusion of this paper is slightly different from Wang et al., while it is consistent with Liang [20], and Liang considered that the largest value of APL appeared in the North China, near the coastal station.

The complicated change of APL is mainly related to the regional geological structure and the unevenness of atmospheric pressure change. This paper statistically analyses the atmospheric pressure in mainland China over different time, and we discover that the larger pressure change of the area are mainly located in the Tibetan plateau and the East China, followed by the Southern part of China and small part of Northeast areas; the APL value of all areas is large except the Tibetan plateau. The phenomenon of small APL value in the Tibetan plateau is likely to be related to the special plate tectonic environment. The transverse wedge of the Indian plate result in the upper mantle outflows response to the atmospheric loading; as a result, there is small deformation loads effect on the earth crust caused by the atmospheric pressure change. Moreover, some scholars

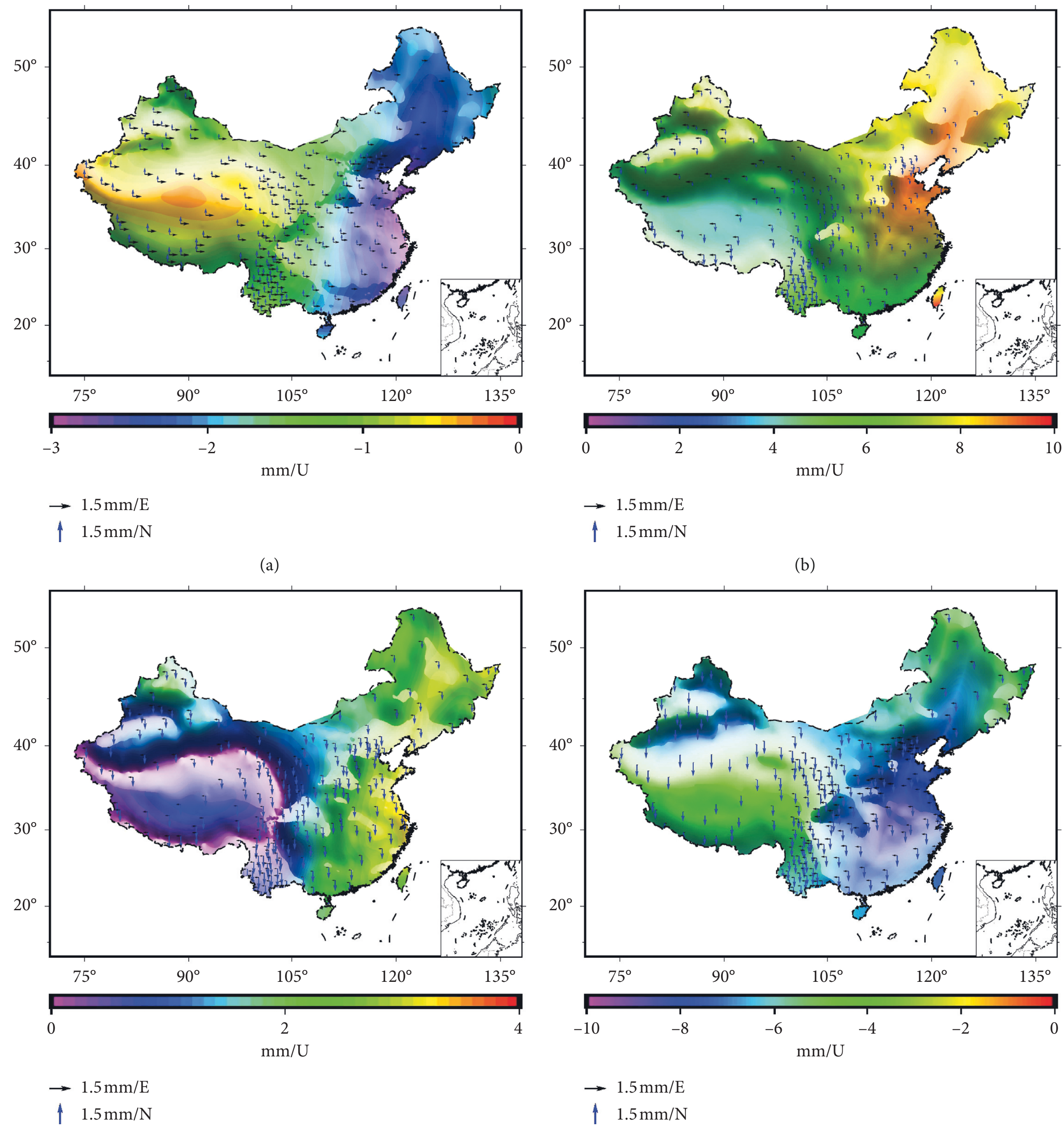


FIGURE 1: Average value of atmospheric pressure loading in mainland China. The figure a, b, c, and d represent four time spans: February to April, May to July, August to October, and November to January of next year; the horizontal arrow indicates the APL of the East-West, the vertical arrow indicates the APL of the North-South, and the background color indicates the APL of vertical direction. Figure number: GS (2016)1570, the same is true of the subsequent figure.

hold the view that the Tibetan plateau crust is very thick through modern earthquake observation [8]. Then, this characteristic may make the regional crust less susceptible to external loads, but this thesis need to be confirmed by more evidence.

The whole horizontal loading displacement value is small, the variation of the APL value of all stations range from 1.5 mm to 3 mm. Compared with the variation of APL in the South-North direction and East-West direction, we can see that the APL value of the two directions show small difference, and the difference is less than 1 mm in whole investigative region. Because the horizontal crustal movement in mainland China is in range of 0–30 mm/a relative to stable Eurasia Plate [27], the loading effect of the atmosphere is relatively negligible.

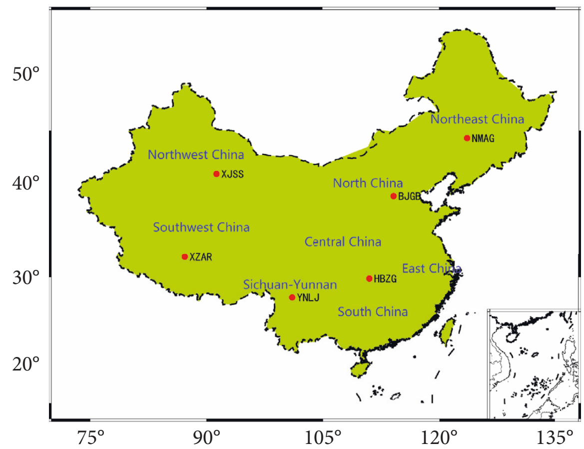


Figure 2: The distribution of region and six stations in mainland China.

In Table 1, the mainland China is divided into nine parts, and we calculate the average value of the biggest variation of the APL value in the direction of positive and negative for the stations. In particular, because Sichuan and Yunnan districts have been the research hotspot in recent years, tectonic movement in the area is very complex. Therefore, it is necessary that this area is studied independently in this paper. In addition, we also extract this kind of stations on the coastline centered within the scope of 0.5° (*about within 55 km of the coastline*) in this paper and calculate the average APL value.

4. Atmospheric Pressure Loading and GNSS Coordinate Time Series

4.1. Changes of Time Series before and after Correction. From the above analysis, it can be seen that the loading deformation greatly affects the vertical direction of the GNSS reference station. Therefore, this paper analyzed the vertical movement characteristics of APL on the GNSS reference station, and the accuracy of these stations' coordinates in vertical direction are less than 3 mm. The corrections of APL are added to the coordinates after their processing by GAMIT/GLOBK software. Six typical stations (see Figure 2) in different regions of mainland China are selected for analysis of APL correction (see Figure 3).

The solid earth tide and pole tide have been corrected in the data processing. The ocean tidal loading and nontidal mass loading greatly affect coastal stations [20, 28–30]. Therefore, the nontectonic crustal loading deformation affecting the continental GNSS stations time series are mainly the atmospheric pressure loading and the snow and soil moisture mass loading.

The station XJBC is located in the Xinjiang region, the station NMAG is located in Northeast China, the station HBZG is located in Central China, and the BJGB is located in North China. The amplitude of the time series of the four stations decreases obviously after correction by APL, especially in Xinjiang regions. Except for the station NMAG, the intercepts and slopes of the other three stations show the same regulation after linear fitting for the corrected time series by using APL and uncorrected time series. The situation is that the slope changes little, while the intercept decreases. But for the station NMAG, the change of slope and intercept is obvious. By analyzing the change of the slopes, the result shows that the APL influence on the regulation of the whole linear movement of the crust in these areas is small and the crust shows an overall upward trend over time. In contrast, by analyzing the change of the intercepts, the result shows that the APL has great influence on the displacement of the vertical movement in these areas.

The station XZAR located in the Tibetan Plateau shows a weak trend of vertical annual movement compared with the above four stations. When the correction of APL is carried out for this station, the amplitude change is small, and the slope and intercept of linear fitting are basically the same for the time series before and after correction. The reason may be related to the special crustal tectonic environment in this area [31]. The station YNLJ located in the Lijiang of Yunnan shows a striking feature, in which the change of amplitude of the time series is small than the original after the APL correction, while the periodicity of this station nearly has no changes by using harmonic fitting. The reason may be that the geological tectonic environment is more complicated and the continental hydrosphere loading in these areas is more serious, for example, the region of Sichuan-Yunnan [32–34].

4.2. Amplitude and RMS Change of Daily Solution before and after Correction. In order to study the amplitude variation of the daily solution time series and vertical velocity of the GNSS site before and after APL correction, the model shown in formula (4) is used and the periodic amplitude and station velocity are estimated based on the maximum likelihood function method [35]. The results are shown in Table 2.

Table 1: Average APL in different regions in mainland China.

Regions/range (°)	Number of site	E/mm	N/mm	U/mm
Northwest China (lon: 72–102, lat: 36–50)	375	−0.19~1.55	−1.34~1.65	−5.32~4.92
Southwest China (lon: 72–97, lat: 25–36)	147	−0.36~2.75	−1.58~2.11	−3.99~5.18
Sichuan-Yunnan of China (lon: 97–107, lat: 21–36)	497	−0.26~2.10	−0.66~1.90	−5.06~5.67
South China (lon: 105–118, lat: 22–29)	130	0.31~2.96	−1.14~1.01	−6.80~7.29
Central China (lon: 107–118, lat: 29–36)	123	−0.37~1.41	−0.64~0.99	−6.37~8.41
East China (lon: 116–124, lat: 29–37)	165	0.34~0.83	−1.56~1.27	−6.51~10.18
North China (lon: 102–119, lat: 36–45)	565	0.30~1.95	−0.79~0.97	−6.97~8.49
Northeast China (lon: 117–136, lat: 40–54)	185	−7.33~1.81	−1.52~1.08	−6.36~10.12
Along the coast (lon: 111–122, lat: 21–41)	270	−0.04~1.42	−2.13~1.28	−8.72~8.68

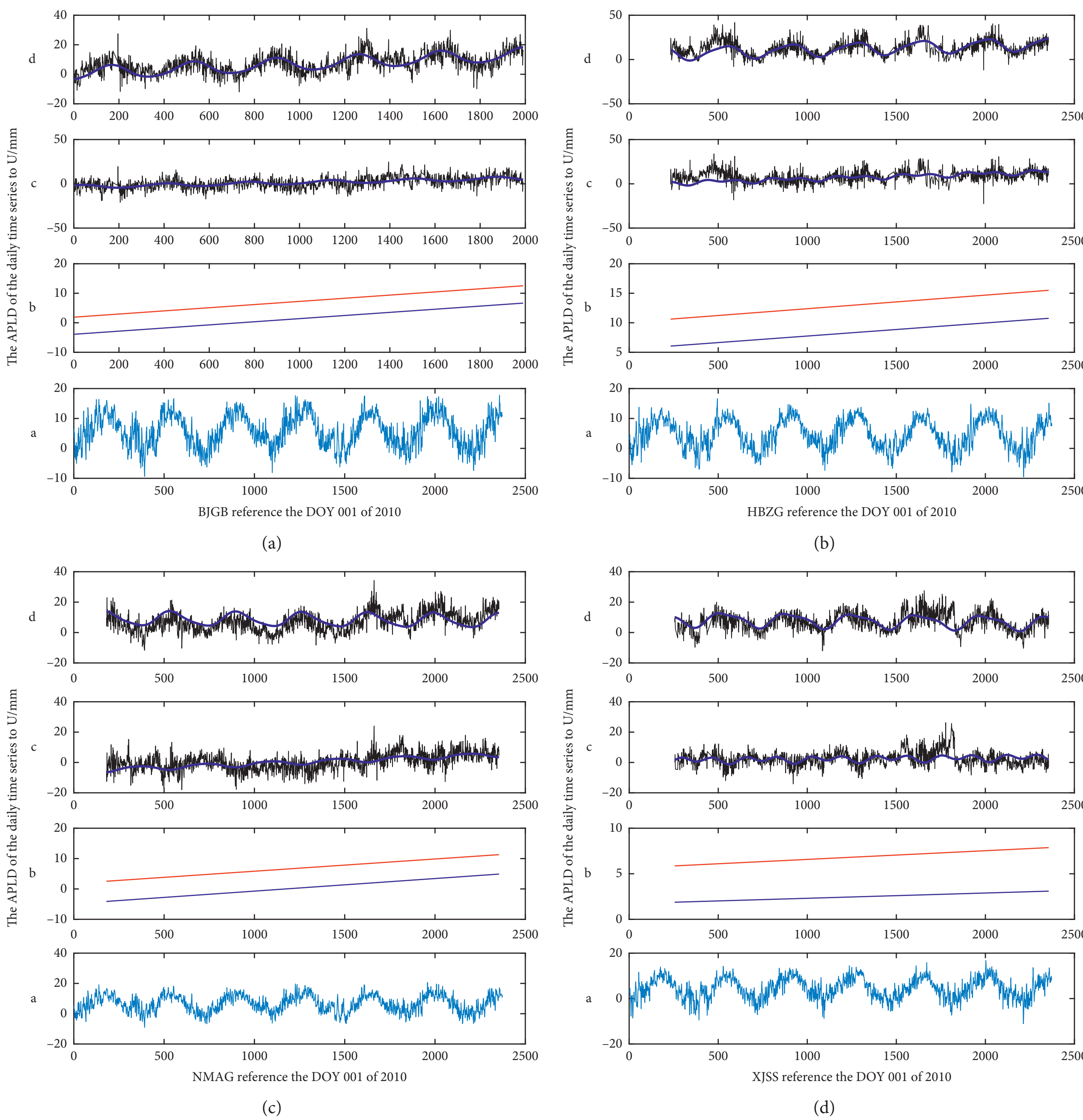
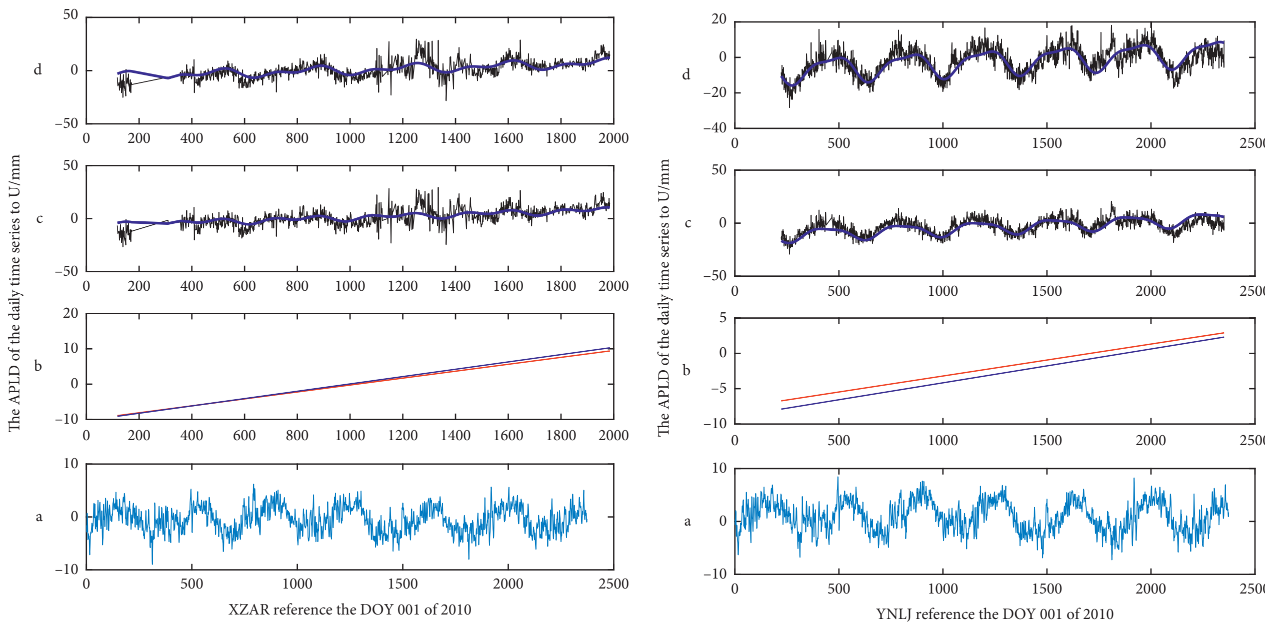


Figure 3: Continued.



(e) (f)

Figure 3: GNSS stations vertical time series changes by atmospheric load correction. (a) The atmospheric loading correction; (b) linear fitting curve before and after correction, respectively (red and blue lines); (c) corrected daily solution time series; and (d) uncorrected daily solution time series, blue curve was obtained by sine function fitting.

$$y(t_i) = a + bt_i + c\sin(2\pi t_i) + d\cos(2\pi t_i) + e\sin(4\pi t_i) + f\cos(4\pi t_i) + \sum_{j=1}^{n_j} g_i H\left(t_i - T_{hj}\right) + v_{t_i}, \tag{4}$$

where t_i is the epoch with single day of GNSS station, the unit is year; a is the first value in the daily solution sequence; b is the linear rate of the GNSS time series; c, d, e, and f are the coefficients of annual and semiannual cycles; g_i is the big jump amplitude; H is the Heaviside function, the value is 0 before the big jump amplitude and is 1 after that; T_{hj} is the epoch of jump; n is the number of jump; v_{t_i} is the observation noise; and the annual fitting amplitude is $\sqrt{c^2 + d^2}$ and the semiannual fitting amplitude is $\sqrt{e^2 + f^2}$.

The six stations selected in Table 2 are from different regions in mainland China. According to the variation of annual and semiannual amplitude obtained by the fitting of daily solution time series before and after correction with model (4), we find that the attenuate degree of the annual motion is serious than semiannual motion of the GNSS site in vertical direction, but the vertical motion of the GNSS station is still dominated by anniversary. It shows that the APL has an important influence on the annual vertical motion of the station. In addition, the amplitude variation of the YNLJ station is significantly smaller than that of other stations, and this may be due to the fact that the site is located in the eastern margin of the Tibetan Plateau, and the geological structure of this area is complex and the continental hydrosphere migration is serious. The vertical speed of the 6 stations is larger than that before correction, which shows that the APL intensifies the vertical motion of the station to some extent, and changed values by about 0.2–1.9 mm/a.

218 stations with optimal solutions and data quality are selected from the Crustal Movement Observation Network of China, and the RMS values of vertical direction in each station before and after the APL correction are calculated, respectively Table 3. The change of the RMS value is about 0.3–1.5 mm except for Southwest China.

The RMS of the daily solution time series in the three directions for the GNSS reference station has changed after the APL correction, and the east-west direction is slightly larger than the north-south direction, which shows that the crustal deformation of EW direction is more serious than the NS direction. For the vertical direction, the change of the RMS value is about 0.2–0.8 mm except for Southwest China for the vertical direction of GNSS station. In addition, it can be seen that the influence of APL on the crust deformation is basically the same for the E or N direction according to the RMS changes in different regions, while the APL influence on the vertical direction varies greatly in mainland China.

5. Correlation Analysis between Atmospheric Pressure Change and Crustal Deformation

One of the methods to study the atmospheric gravity admittance is to calculate the influence of the pressure changes on the ground gravity by the loading Green's function theory and make a convolution of the earth's Green's function with the global pressure [21]. The gravity correction value can be obtained according to the variation of atmospheric pressure and atmospheric gravity admittance in the region.

Table 2: Fitting parameters of annual and semiannual before and after correction.

SITE	Annual Amplitude (mm)		Semiannual Amplitude (mm)		— Velocity (mm/a)	
	Uncorrected	Corrected	Uncorrected	Corrected	Uncorrected	Corrected
BJGB	4.51	1.96	0.55	0.29	1.40	1.81
YNLJ	6.66	5.86	2.12	1.53	1.78	2.71
HBZG	7.15	1.71	1.39	1.66	1.98	2.22
NMAG	4.54	1.50	0.82	0.22	−0.25	1.67
XZAR	3.13	1.60	2.35	1.88	2.51	2.72
XJSS	4.41	0.99	1.39	1.79	−0.44	0.36

Table 3: Change of the RMS absolute value before and after correction.

Regions	Number of site	N-RMS	E-RMS	U-RMS
East China	14	0.068	0.578	0.456
Sichuan-Yunnan	59	0.144	0.529	0.193
Northeast China	20	0.114	0.608	0.235
North China	38	0.122	0.553	0.526
South China	15	0.146	0.575	0.529
Central China	15	0.143	0.536	0.804
Northwest China	40	0.311	0.441	0.216
Southwest China	11	0.420	0.428	1.517
Along the coast	25	0.149	0.617	0.624

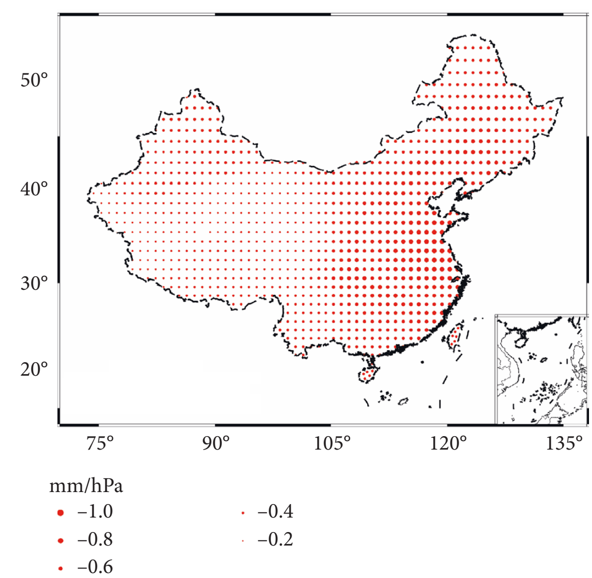


Figure 4: Relationship between load deformation and pressure change at stations.

Based on the similar method, we get the correlation between atmospheric pressure change and vertical crustal deformation. Firstly, the APL at 2229 GNSS reference stations is calculated according to the spherical harmonic function and the loading theory with the data of global atmospheric pressure variation. Secondly, the global atmospheric pressure variation is interpolated into the station by spline interpolation. Thirdly, the loading deformation and the atmospheric pressure change of the daily value of 2010.1–2016.6 is averaged at every station. Ultimately, the relative change relation can be acquired by making ratio. In order to reflect the distribution characteristics more clearly, we make the grid interpolation of $1^\circ \times 1^\circ$ (see Figure 4).

The extent of vertical deformation of the crust under APL can be roughly reflected in Figure 4. As shown in the figure, the deformation value of the crust is the largest in the north-eastern of North China, the Northeast China, and the eastern area of Central China, and the magnitude is about 6~8 mm when the atmospheric pressure changes 1 kPa in these areas. The degree of deformation gradually decreases from eastern to western region in mainland China. The magnitude of the Qinghai Tibet Plateau is about −0.45~−0.3 mm/hPa, but the annual periodic change of atmospheric pressure is very significant. The main reason may be that it is related to the variation characteristics of the upper crust, lower crust, and middle mantle in the Tibet Plateau. The magnitude of the Northeast China is about −0.6~−0.75 mm/hPa, but the change of the atmospheric pressure is not more remarkable than Qinghai Tibet Plateau. This situation may be mainly related to deep geological structure and the low velocity matter distribution of crust and mantle, as well as cold climate conditions in this area [36]. For the Northwest arid region, the deformation value is about 5.5 mm when the atmospheric pressure changes 1 kPa.

6. Conclusions

The effect of atmospheric pressure changes on crustal deformation in the mainland China are calculated by using a spherical harmonic expansion and GNSS reference stations. Based on these, the characters of APL on vertical time series of GNSS reference stations in different regions are studied:

(1) Based on the analysis of regional APL characteristics, we find that northern area of East China, southeastern area of North China, and Northeast China are greatly affected by APL, the maximum correction value can reach 24 mm. The area least affected by the APL is the Qinghai Tibet Plateau and surrounding regions, and the loading deformation value is about 10 mm. By comparing the results of this paper with the results obtained by Dach and Steigenberger [37]

who used the Vienna APL model and global IGS stations to compute the APL correction, it can be concluded that the average difference is about 1.5 mm in the southwestern region and about 3.0 mm in the northwestern region of mainland China. For horizontal direction, the difference of APL corrections is consistent and the average difference is less than 1.0 mm.

(2) According to the change of vertical time series of GNSS reference station in different regions before and after APL correction, the loading deformation caused by atmospheric disturbances is very serious in Northwest China and Northeast China, and the amplitude fluctuation is greatly reduced after correction. But for the Sichuan-Yunnan region, the amplitude fluctuation becomes larger after correction, and the result may be caused by abrupt vertical movements of the crust and the changes in watersheds.

(3) Based on the vertical loading deformation of GNSS stations and the variation of atmospheric pressure from January 2010 to June 2016, the correlation between pressure change and crustal deformation is obtained. The results indicate that the deformation value of the regions that between 30 and 40 degrees latitude and 110 and 120 degrees longitude are larger than others when the pressure changes the same. Especially in the eastern part of Central China, the value of vertical deformation can reach 8.2 mm when the atmospheric pressure changes 1 kPa. In addition, the atmospheric loading correction value at the station can be estimated by using the correlation and atmospheric pressure change.

Data Availability

The data used to support the findings of this study are available from the first author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Yamin Dang, Changhui Xu, and Caiya Yue conceived and defined the research sheme. Shouzhou Gu verified the feasibility of the method and implemented the software algorithm. Huayang Dai and Changhui Xu checked the data processing results and wrote the manuscript. Caiya Yue helped to revise the manuscript and modified some figures and tables.

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