A Study of the Impact of Atmospheric Pressure in Eastern Qilian Mountains on Vertical Deformation at GNSS Stations

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Abstract. The change of the earth's surface environmental load is an important factor that causes the crustal short-term movement. The project address is in the eastern part of Qilian Mountain, and we take the crustal vertical deformation and gravity changes affected by load changes as the research object. Based on the crustal load deformation theory, we use the data of GNSS continuous reference stations and meteorological stations in the region to study the evolution between atmospheric load changes and vertical crustal movement in the region from 2012 to 2017. The results show that the atmosphere in the eastern part of the Qilian Mountains is affected by atmospheric load periodically and varies with the seasons. On average, atmospheric pressure is low in summer and high in winter, resulting in annual periodic crustal vertical deformation, while the crustal uplifts in summer and declines in winter. The crustal deformation in most areas is the largest around January and August, and there are certain differences in crustal deformation in different areas.

1. Introduction

The change of the earth's surface environmental load is an important factor that causes the short-term crustal movement. The change of atmospheric pressure distribution is the main source affecting the vertical crustal deformation[1,2]. GNSS continuous monitoring station can observe the changing process of the earth's crust under load. Therefore, studying the relationship between atmospheric pressure changes and vertical deformation is an important way to explore the laws of regional crustal movement[3].

This project selects the eastern part of the Qilian Mountains, and we will take the vertical crustal deformation and gravity changes affected by load changes as objects. According to the crustal load deformation theory, we use the data of GNSS continuous reference stations and meteorological stations in the region to analyze and study the evolution between atmospheric load changes and vertical crustal movement in the region from 2012 to 2017.

2. Theoretical relationship between atmospheric pressure change and vertical deformation of GNSS station

2.1. Crustal load deformation
The crustal deformation caused by the load is the sum of the load deformation per unit particle. Therefore, calculating the influence of unit point source is the basis for calculating the overall load deformation [4,5].

In Farrell’s research, the convergence problem of the surface loading Green’s functions was solved. Its research mentioned that if the spherical harmonic expansion of the surface load is known, then the radial deformation of the earth under load can be calculated using Equation 1:

$$u(\varphi, \lambda) = \frac{3}{p_e} \sum_{n=0}^{\infty} \frac{\hat{h}_n}{2n+1} \frac{\partial q_n(\varphi, \lambda)}{\partial \psi} (1)$$

$$q_n(\varphi, \lambda) = \sum_{m=0}^{\infty} \left[ q_{n,m}^e(\varphi, \lambda) \cos m\lambda + q_{n,m}^s(\varphi, \lambda) \cos m\lambda \right] p_{n,m} \sin \varphi (2)$$

where $u(\varphi, \lambda)$ is radial and horizontal deformation. $\varphi$ and $\lambda$ are the remaining latitude and longitude of the calculated point, and $\psi$ is the angular distance from the point $(\varphi, \lambda)$ to the load point. In addition, $p_e$ is the density of the earth, and $\hat{h}_n$ is the loading Love Numbers. $q_n(\varphi, \lambda)$ is the spherical harmonic expansion of the load value, and $q_{n,m}^e(\varphi, \lambda)$ and $q_{n,m}^s(\varphi, \lambda)$ are the Stokes coefficients of the n-order expansion. $p_{n,m}$ is the associated Legendre function.

2.2. Sources and characteristics of monitoring data
We applied for pressure data from the China Meteorological Data Network. The regional GNSS monitoring data is the data of the tectonic environment monitoring network in mainland China.

At present, the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) provide commonly used surface pressure reanalysis data. The sampling frequency of air pressure data provided by these analysis centers is generally 6 hours.

After comparative analysis, we finally chose to apply Kriging interpolation method to interpolate the atmospheric pressure data of the weather station as regional grid data.

3. Numerical analysis of atmospheric pressure spatiotemporal changes and vertical deformation of GNSS stations

3.1. Spatiotemporal changes of atmospheric pressure in the Qilian Mountains
We selected multiple GNSS stations for calculation, and selected the Gaolan Gansu GSGL, Lanzhou Gansu GSLZ, Minqin Gansu GSMQ, Jingtai Gansu GSJT stations for analysis and research. In this paper, the latitude and longitude ranges are 100°~104°E, 35°~39°N. For the study area, we selected the 72-month atmospheric pressure interpolated weather station data from 2012 to 2017 to obtain the atmospheric pressure regional transition process. According to the changes in atmospheric pressure over the past six years, it can be seen that the overall changes tend to stabilize.

![Figure 1. Time Series Change of Atmospheric Pressure at GNSS stations from 2012 to 2017](image)

3.2. Vertical deformation of GNSS stations in the area
3.2.1 Part of the site change process. In the selected latitude and longitude range, we still select GSGL, GSLZ, GSMQ, and GSJT stations as representatives for data analysis. Some changes are shown in Figure 2.

![Figure 2. Time Series Change of Height at GNSS Stations](image)

From the figure, we can find that the scatter items from 2012 to 2017 are relatively stable. After the period reconstruction, the fitting curve is correctly fitted to the scatter item, and the overall linear change over 6 years is relatively stable. According to the data, it can be concluded that the rate of earth elevation changes at the GSMQ station, GSLZ station, GSJT station and GSGL station is -1.98mm/a, -2.91mm/a, 0.99m/a, 1.48mm/a, respectively.

3.2.2 Regional crustal deformation process. Comparing the changes in 2012 and 2017, we can find from the vertical deformation charts of the GNSS stations in February, April, June, August, October, and December each year that the vertical deformation variable in this area in 2012 is the largest in June. The maximum value is 9mm. The vertical deformation reached the minimum in December, with a minimum of 1mm.

![Figure 3. Regional Crustal Vertical Deformation in 2012](image)
3.3. The relationship between the spatial and temporal changes of atmospheric pressure and the vertical deformation of the GNSS station

We calculated the crustal load deformation in order to evaluate the relationship between the atmospheric pressure time series changes in the eastern Qilian section and the vertical deformation of the GNSS station. We selected 6 years of atmospheric pressure to interpolate GNSS station data, and then compared with the corresponding vertical deformation variables.

![Figure 4. Ground Gravity Change at GNSS stations](image)

In order to obtain the relationship between atmospheric pressure and vertical deformation, this paper converts the effect of atmospheric pressure on the earth's crust into corresponding equivalent levels, and it inverts the process of ground gravity changes. Figure 4 shows the normal gravity changes retrieved from GNSS continuous reference stations. The calculated value range is shown in the tables.

| Stations | GSGL | GSJT | GSLZ | GSMQ |
|----------|------|------|------|------|
| Mean     | 3.96 | 4.16 | 3.92 | 4.34 |
| Standard Deviation | 2.74 | 2.99 | 2.75 | 3.17 |
| Minimum  | -0.31 | -0.52 | -0.39 | -0.64 |
| Maximum  | 8.88  | 9.48 | 8.79 | 10.02 |

| Stations | GSGL | GSJT | GSLZ | GSMQ |
|----------|------|------|------|------|
| Mean     | 2.73 | 3.24 | 3.01 | 3.59 |
| Standard Deviation | 1.88 | 2.53 | 2.27 | 2.89 |
| Minimum  | -0.22 | -0.89 | -0.71 | -1.17 |
| Maximum  | 6.27  | 7.86 | 7.15 | 8.86 |

It can be seen that atmospheric pressure changes, vertical crustal deformation, and ground gravity have obvious correlations, and the characteristics of changes with annual cycles are more obvious. As shown in Figure 5, there are obvious rules between atmospheric pressure, vertical crustal deformation, and ground gravity changes. For example, as atmospheric pressure increases or decreases, the vertical deformation decreases or increases accordingly, showing opposite changes.
Figure 5. Time Series Change of Atmospheric Pressure, Vertical Deformation and Normal Gravity at GNSS Stations

The left side of the figure is marked as the atmospheric pressure change value, and the right side is marked as the vertical deformation and ground gravity change, which are the influence of the atmosphere on the vertical deformation of the crust in the region. We can use the northeastern margin of the Qinghai-Tibet Plateau and the Qilian Mountains as the boundary, and the least amount of influence on the Tibetan Plateau is about 6.1 mm. In the northeastern part of the dividing line, the annual change has increased significantly, which is 12.2 mm.

We can find that atmospheric pressure changes, vertical crustal deformation, and ground gravity have obvious correlations. They usually change on a yearly basis. For example, atmospheric pressure is low in summer and high in winter, while the crust is rising in summer and falling in winter. In addition, ground gravity increases in summer and decreases in winter. The periodic vertical deformations produced by the earth's crust range from 5mm to 10mm.

4. Conclusions

The change of atmospheric pressure distribution is the main source affecting the vertical crustal deformation. By observing the changing process of the crustal formation at the GNS monitoring station, we can draw the following conclusions for the study area (100°~104°E, 35°~39°N).

Atmospheric load is the main environmental load factor, and periodic changes are significant. According to the statistical results from 2012 to 2017, the region has a distinctive annual cycle. Atmospheric pressure is low in summer and high in winter, and the crust is uplifted in summer and declined in winter, resulting in annual periodic vertical crustal deformation. Atmospheric load dominates in summer and winter, and the rate of change of the crustal load deformation increases during the period of alternating seasons.

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