

## Impact Analysis of Bedrock Thermal Expansion on Three-Dimensional Annual Surface Deformation in Southwest China: Postprint

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### Abstract

The Global Navigation Satellite System (GNSS) can monitor and obtain surface deformation time series, wherein the annual signals contain, in addition to loading deformation, the thermal expansion effect of bedrock caused by surface temperature variations. Using a global three-dimensional thermoelastic deformation model, this study estimates the thermal expansion effects in the U, E, and N directions at 39 Crustal Movement Observation Network of China (CMONOC) stations in Southwest China, and analyzes the consistency between GNSS time series and surface loading deformation reflected by GRACE (Gravity Recovery and Climate Experiment) and GRACE Follow-On (GRACE-FO) satellite gravimetry observations before and after thermal expansion effect correction. The results show that after applying thermal expansion effect correction, the consistency between the GNSS vertical component (U direction) and satellite gravimetry results slightly decreases; while the consistency in the horizontal component E direction shows some improvement, but a more significant decrease occurs in the N direction. The research results obtained for Southwest China in this study are inconsistent with existing global or large-scale regional studies, indicating that the accuracy of estimating thermal expansion effects in different regions using global thermoelastic deformation models requires further evaluation, and its impact on three-dimensional surface deformation also warrants in-depth follow-up research.

### Full Text

### Preamble

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## Analysis of the Impact of Bedrock Thermal Expansion on Three-Dimensional Surface Annual Deformation in Southwest China

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### Abstract

The Global Navigation Satellite System (GNSS) can monitor and obtain time series of surface deformation, wherein the annual signals include not only load deformation but also the effect of bedrock thermal expansion caused by surface temperature variations. Using a global three-dimensional thermoelastic deformation model, we estimate the thermal expansion effects at 39 Crustal Movement Observation Network of China (CMONOC) stations in Southwest China in the three directions (U, E, N) and analyze the degree of agreement between GNSS time series (before and after thermal expansion correction) and surface load deformation reflected by GRACE (Gravity Recovery and Climate Experiment) and GRACE Follow-On (GRACE-FO) satellite gravity observations. The results show that after applying thermal expansion corrections, the agreement between the vertical component (U direction) of GNSS and satellite gravity results is slightly weakened; while the agreement in the horizontal E direction improves to some extent, it shows a significant decrease in the N direction. The findings for Southwest China in this study are inconsistent with existing global or large-scale regional studies, indicating that the accuracy of estimating thermal expansion effects in different regions using global thermoelastic deformation models requires further evaluation, and its impact on three-dimensional surface deformation warrants subsequent in-depth research.

**Keywords:** thermal expansion effect; surface load deformation; GNSS; GRACE; GRACE-FO

### 1 Introduction

The Global Navigation Satellite System (GNSS) provides high-precision surface deformation observation data. By processing GNSS position time series measured at ground stations, we can analyze three-dimensional surface deformation characteristics, providing data support for establishing and maintaining terrestrial reference frames, as well as for research in seismology, hydrology, and global climate change. GNSS deformation observations contain multiple geophysical signals, primarily including plate motion in the station region and load deformation caused by surface mass changes. Surface load mass changes are further divided into anthropogenic mass migration (such as groundwater and

coal mining, lake reclamation, etc.) and natural surface mass seasonal changes caused by factors like precipitation, ocean currents, and atmospheric activity. Additionally, periodic thermoelastic deformation of observation station monuments and bedrock caused by surface temperature variations can reach several millimeters in amplitude. Therefore, the influence of thermal expansion effects cannot be ignored when using GNSS deformation observations for load effect studies.

Thermal expansion effect refers to the phenomenon of object deformation caused by periodic changes in Earth' s surface temperature. Since Berger proposed a two-dimensional thermoelastic deformation model in 1975, many studies have explored this topic in depth. Dong et al. developed a method for calculating vertical thermoelastic deformation of bedrock, showing that the maximum annual amplitude in the global vertical direction does not exceed 0.56 mm. Yan et al. further analyzed 86 Global Positioning System (GPS) stations and found that the maximum annual amplitude of vertical deformation caused by bedrock thermal expansion can reach 1.3 mm. Yan et al. studied the impact of thermoelastic deformation on Chinese GNSS stations, finding that vertical thermoelastic deformation can reach up to 1 mm. Jiang et al. conducted fitting analysis on thermoelastic deformation time series, concluding that annual variation is the main signal. Jia et al. jointly analyzed the impact of thermal expansion on surface vertical deformation using GPS and GRACE data, showing that correcting for thermal expansion can improve consistency between the two. These studies demonstrate that surface annual deformation caused by thermal expansion is a non-negligible factor in station displacement. However, the above research has focused on vertical surface deformation and was based on half-space Earth models, whereas the actual Earth is closer to a sphere. Therefore, Fang et al. proposed in 2014 a calculation method for three-dimensional deformation in horizontal and vertical directions caused by thermal expansion effects based on a spherical model under geocenter-fixed constraints. Xu et al. used this method to calculate thermoelastic deformation, showing that the maximum annual amplitude in the vertical direction can reach 3 mm and 1.5 mm in the horizontal direction. Wei et al. used data from global GPS stations to calculate thermoelastic deformation using this method and compared it with GPS deformation after subtracting load deformation calculated from GRACE data, showing good spatial consistency in the N direction. Tan et al. calculated three-dimensional thermoelastic deformation in mainland China using this method, superimposing the annual surface variation information caused by temperature changes onto the annual signals inverted from GRACE and mass load models, and then compared them with GNSS deformation. The results also proved that considering thermal expansion effects improved the agreement between both and GNSS.

GRACE satellites, jointly developed by NASA and GFZ, were launched in March 2002 and terminated in October 2017 for detecting Earth' s gravity field and its time variations. Their successor, GRACE-FO, was launched in May 2018 and continues to operate. GRACE/GRACE-FO adopts a polar orbit design for all-weather observation of the global gravity field. By analyzing the distance,

velocity, and acceleration data between the two satellites in orbit, they provide a new method for monitoring global gravity field changes. GRACE/GRACE-FO science data release agencies provide monthly Earth gravity field model data, including GSM data that gives spherical harmonics coefficients (SH) describing Earth's gravity field, which can be used to calculate geoid and its temporal variations. Due to errors, GRACE/GRACE-FO monthly gravity field model data require preprocessing such as low-degree term replacement and filtering before use, but filtering may cause signal leakage and distortion. In recent years, GRACE/GRACE-FO data processing agencies have also launched mascon data products, displaying gravity field changes in the form of global grid mass changes (equivalent water height). The data have already undergone low-degree term replacement, post-glacial rebound correction, and other processing, requiring no filtering operations and can be directly used for analysis and research of surface mass changes.

By comparing GNSS observation time series with surface load deformation time series calculated from GRACE/GRACE-FO, we can verify the reliability of GRACE/GRACE-FO data on one hand, and on the other hand, use them for more reasonable analysis and interpretation of non-tectonic deformation. In GNSS surface deformation time series, besides load deformation caused by surface mass changes, bedrock thermoelastic deformation caused by temperature changes is also an important signal, especially in regions with obvious annual (seasonal) temperature variations where its impact cannot be ignored. Therefore, to more accurately analyze various factors in GNSS deformation, besides considering surface mass load change effects, we also need to account for thermal expansion effects.

In GNSS deformation analysis, previous research on thermal expansion effects has mainly focused on the vertical direction and on global or large-scale regions, with relatively few studies on local areas. To analyze the impact of thermal expansion effects on GNSS station deformation in local areas, this paper selects Southwest China, adopts the three-dimensional thermoelastic deformation calculation method based on spherical models, and uses global temperature change data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), GRACE/GRACE-FO SH products and mascon products released by the Center for Space Research (CSR) at the University of Texas, and GNSS three-dimensional deformation observation data solved by the Crustal Movement Observation Network of China (CMONOC). The aim is to analyze the consistency changes between GNSS deformation time series and three-dimensional deformation calculated by GRACE/GRACE-FO before and after thermal expansion correction, in order to better analyze and interpret the impact of thermal expansion effects caused by temperature changes on GNSS data.

## 2.1 GNSS Data

The GNSS data used in this study come from the Crustal Movement Observation Network of China (CMONOC). CMONOC uses GAMIT/GLOBK software

to solve GNSS observation data to obtain deformation time series. Based on geographical location, CMONOC divides national observation stations into 7 sub-networks, with common observation stations between each sub-network. The common observation stations and International GNSS Service (IGS) observation stations around China form an integrated large network, which is constrained to the International Terrestrial Reference Frame (ITRF) through IGS stations. Using GAMIT/GLOBK processing, we obtain daily relaxation solutions for observation stations, which are free-network solutions. Through seven-parameter similarity transformation using globally distributed ITRF reference frame points, they are finally constrained to the ITRF2008 frame.

This study selects CMONOC observation stations located in Southwest China (longitude  $86^{\circ}$ - $109^{\circ}$ , latitude  $21^{\circ}$ - $34^{\circ}$ ) for analysis. Before using CMONOC GNSS observation data, a series of preprocessing steps were performed: first, stations with poor observation quality and insufficient observation epochs were removed; second, jumps caused by instrument replacement and coseismic displacement were detected and corrected; finally, gross errors were eliminated using the three-sigma criterion. To maintain consistency with the data baseline and monthly time span deducted from GRACE/GRACE-FO data, further processing of GNSS data was conducted: the average value during 2004.0-2010.0 was subtracted; according to the monthly time span provided by GRACE/GRACE-FO, the number of GNSS daily data within that month was determined. If it reached more than half of the days corresponding to that month, it was converted to monthly data by equal-weight averaging. After this series of data processing, 39 GNSS observation stations were finally selected, with their coordinates and time span details shown in Table 1 .

## 2.2 GRACE/GRACE-FO Data

The GRACE/GRACE-FO data used in this study all come from CSR, including 96-degree GSM(SH), 180-degree GAC and GAD spherical harmonics coefficient data products (<ftp://rz-vm152.gfz-potsdam.de>), and RL06.2 mascon grid equivalent water height data (<http://www2.csr.utexas.edu>).

For CSR SH data, a series of preprocessing steps were performed before use. Since GRACE/GRACE-FO satellites cannot observe geocenter motion, TN13 data were used to replace C10, C11, and S11 terms. Due to the satellite's orbital design characteristics, GRACE/GRACE-FO data are insensitive to low-degree terms, so Satellite Laser Ranging (SLR) data were used to replace C20 and C30 terms. To reduce north-south stripe errors and decrease high-degree coefficient noise, destriping filtering and 300 km Gaussian smoothing were applied. CSR-provided AOD1B RL06 GAC data were used for non-tidal atmospheric and ocean corrections. Data provided by Peltier were used for Glacial Isostatic Adjustment (GIA) correction.

CSR mascon data already include relevant data replacement and error corrections. TN-13a data were used to correct degree-1 geocenter motion terms. SLR

TN14 data were used to replace the C20 term of GRACE/GRACE-FO data and the C30 term of GRACE-FO data. GIA effects were corrected based on the ICE-6G\_D model. For oceanography-related research, AOD1B GAD data had been added back. To reduce the impact of land-ocean signal leakage effects, mascon mass blocks crossing land-ocean boundaries were solved in two parts. Simultaneously, to improve the accuracy of land-ocean boundary values, data were finally released at  $0.25^\circ$  latitude-longitude intervals. CSR mascon data are anomalies relative to the average between 2004.0-2010.0. To maintain consistent temporal reference frames, the same time period average was subtracted from CSR SH data to obtain monthly mass changes.

### 2.3 Temperature Data

This study utilized Earth surface skin temperature monthly mean data provided by ECMWF (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means>), published in  $0.1^\circ \times 0.1^\circ$  grid format, smoothed to  $0.5^\circ \times 0.5^\circ$  temperature data, with a time span of 2010.0-2022.0, totaling 12 years.

### 2.4 Deformation Calculation Theory

According to load deformation theory, mass changes on Earth' s surface cause load deformation of the crust at observation stations. Considering mass changes on a global scale, using Green' s functions for convolution integration and corresponding transformations, we can obtain methods for calculating three-dimensional surface load deformation using GRACE/GRACE-FO SH data:

$$e(\theta, \phi) = \sin \theta \sum_{l=0}^{\infty} \sum_{m=0}^l \frac{h_l}{1+k_l} \tilde{P}_{lm}(\cos \theta) [\Delta C_{lm} \cos(m\phi) + \Delta S_{lm} \sin(m\phi)]$$

$$n(\theta, \phi) = -a \sum_{l=0}^{\infty} \sum_{m=0}^l \frac{l_l}{1+k_l} \frac{\partial \tilde{P}_{lm}(\cos \theta)}{\partial \theta} [\Delta C_{lm} \cos(m\phi) + \Delta S_{lm} \sin(m\phi)]$$

$$u(\theta, \phi) = a \sum_{l=0}^{\infty} \sum_{m=0}^l \frac{h_l}{1+k_l} \tilde{P}_{lm}(\cos \theta) [\Delta C_{lm} \cos(m\phi) + \Delta S_{lm} \sin(m\phi)]$$

where  $e(\theta, \phi)$ ,  $n(\theta, \phi)$ , and  $u(\theta, \phi)$  represent load deformation at a surface point in the east-west, north-south, and vertical directions, respectively.  $a$  is Earth' s radius,  $\theta$  is colatitude,  $\phi$  is longitude,  $\Delta C_{lm}$  and  $\Delta S_{lm}$  are dimensionless Stokes spherical harmonics coefficients published by GRACE/GRACE-FO relative to a certain time period average,  $\tilde{P}_{lm}$  is the fully normalized Legendre function of

degree  $l$  and order  $m$ , and  $h_l, l_l, k_l$  are the corresponding load Love numbers. This study uses load Love numbers based on the PREM Earth model.

When using mascon data to calculate load deformation, we first use global grid equivalent water height data from mascon to calculate spherical harmonics coefficients corresponding to surface density changes through integration:

$$\Delta\hat{C}_{lm} = \frac{1}{4\pi a^2 \rho_w} \int_{\Omega} q(\theta', \phi') \tilde{P}_{lm}(\cos \theta') \cos(m\phi') d\sigma$$

$$\Delta\hat{S}_{lm} = \frac{1}{4\pi a^2 \rho_w} \int_{\Omega} q(\theta', \phi') \tilde{P}_{lm}(\cos \theta) \sin(m\phi') d\sigma$$

where  $\theta'$  is colatitude of the load point,  $\phi'$  is longitude of the load point,  $q(\theta', \phi')$  is mass change at the load point (i.e., GRACE/GRACE-FO mascon equivalent water height data), and  $\rho_w$  is water density.

Then convert to spherical harmonics coefficients for geoid change:

$$\Delta C_{lm} = \frac{3\rho_w}{\rho_e} \frac{1+k_l}{2l+1} \Delta\hat{C}_{lm}$$

$$\Delta S_{lm} = \frac{3\rho_w}{\rho_e} \frac{1+k_l}{2l+1} \Delta\hat{S}_{lm}$$

where  $\rho_e$  is Earth' s average density.

For ocean area mass changes, since mascon data only undergo partial restoration, to maintain consistency with signals contained in GNSS surface deformation observations, this study includes atmospheric and ocean mass change signals by subtracting GAD and adding back GAC data. Finally, equations (1)-(3) are used to calculate three-dimensional surface load deformation obtained from GRACE/GRACE-FO mascon.

Finally, three-dimensional thermoelastic deformation caused by surface temperature changes is obtained through equation (7):

$$\mathbf{U}(\theta, \phi) = \sum_{n=0}^{\infty} \sum_{m=-n}^n [\hat{r}U_{nm}(r) + V_{nm}(r)\nabla_1] Y_{nm}(\theta, \phi)$$

$$\nabla_1 = \hat{\theta} \frac{\partial}{\partial \theta} + \hat{\phi} \frac{1}{\sin \theta} \frac{\partial}{\partial \phi}$$

where  $a$  is Earth' s radius. When  $r = a$ :

$$U_{nm}(a) = e^{i(\omega t - \pi/4)} \beta T_{nm} \frac{1+\sigma}{1-\sigma} [1 + A_n(n+2 - \Pi_n) + nB_n]$$

$$V_{nm}(a) = e^{i(\omega t - \pi/4)} \beta T_{nm} \frac{1 + \sigma}{1 - \sigma} [A_n + B_n]$$

where  $\mathbf{U}(\theta, \phi)$  represents total deformation at a point with colatitude  $\theta$  and longitude  $\phi$  caused by temperature changes,  $U_{nm}(a)$  and  $V_{nm}(a)$  represent radial (vertical) and horizontal deformation, respectively, and  $\hat{r}$ ,  $\hat{\theta}$ ,  $\hat{\phi}$  represent unit vectors in the radial, latitudinal (north-south), and longitudinal (east-west) directions.  $\eta$  is thermal diffusivity with a value of  $1 \times 10^{-6}$  m/s,  $\omega$  is the angular frequency of annual temperature variation with a value of  $1 \times 10^{-7}$ /s,  $\beta$  is thermal expansion coefficient with a value of  $1.6 \times 10^{-5}/^\circ\text{C}$ ,  $\sigma$  is Poisson's ratio with a value of 0.2662, and  $A_n$ ,  $B_n$ ,  $\Pi_n$  are constants related to  $\sigma$ . Notably, the  $-\pi/4$  term indicates a phase delay between deformation caused by temperature changes and temperature variation itself.

### 3.1 Impact of Bedrock Thermal Expansion on Consistency Between GNSS and GRACE/GRACE-FO Three-Dimensional Deformation

This study first quantitatively estimated three-dimensional surface deformation caused by bedrock thermal expansion effects. Figure 1 [Figure 1: see original paper] shows the annual amplitude and phase of thermoelastic deformation in Southwest China in the U, E, and N directions. In the U direction, the annual amplitude ranges from 0.0 to 1.8 mm, showing spatial distribution characteristics of large amplitude in the Sichuan-Tibet-Qinghai border region and small amplitude in the southern Yunnan-Guangxi region. The annual phase distribution ranges from  $55.8^\circ$  to  $238.2^\circ$ , but except for a small part of southern Guangxi, thermoelastic deformation in the U direction mostly peaks around August. In the E direction, the annual amplitude is generally small, ranging only from 0.0 to 0.6 mm, with annual phase ranging from  $44.2^\circ$  to  $326.7^\circ$ . Thermoelastic deformation in the E direction peaks around March in some parts of central Tibet, while in most other areas it peaks from July to September. In the N direction, the annual amplitude distribution ranges from 0.8 to 1.8 mm, being larger in southeastern Tibet, the Sichuan-Yunnan-Tibet border area, and southern Guangxi. The annual phase ranges from  $32.3^\circ$  to  $55.1^\circ$ , with thermoelastic deformation in the N direction peaking in February.

This study uses RMS reduction rate, annual amplitude reduction rate, and correlation coefficient of GRACE/GRACE-FO data relative to GNSS data to evaluate the consistency between the two datasets. To show the absolute magnitude of consistency between GRACE/GRACE-FO deformation and GNSS deformation on maps, taking deformation calculated from CSR SH data as an example, the RMS reduction rate, annual amplitude reduction rate, and correlation coefficient results relative to GNSS deformation data after thermal expansion correction are shown in Figure 2 [Figure 2: see original paper]. The results show the following characteristics: the consistency between the two datasets

in the U direction is relatively good, with all three parameters generally being larger, particularly significant at stations in Yunnan region, but relatively poor in Sichuan region. The three parameters in the E direction show both positive and negative values, significantly smaller than those in the U direction, indicating that the consistency between the two datasets in the U direction is higher than in the E direction, with relatively good performance in Sichuan region but unsatisfactory results in western Yunnan. However, the results in the N direction show large differences between the two datasets and are significantly weaker than in the U and E directions. The RMS reduction rate and annual amplitude reduction rate are less than zero at many stations, especially showing unsatisfactory performance in Sichuan region, with only slightly better results in parts of Yunnan. Overall, although thermal expansion effects are more significant in the vertical direction than in the horizontal direction in Southwest China, vertical load deformation is also larger and constitutes the main signal in GNSS deformation. Therefore, the consistency of the three parameters is higher after thermal expansion correction. Additionally, the comparison results of the three parameters show no obvious correlation with the geographical distribution of stations.

Note: Annual amplitude  $A$  and annual phase  $\phi$  are defined according to  $A \cos[\omega(t - t_0) - \phi]$ , where  $t_0$  is 2008.0 and  $\omega$  is the angular frequency with a value of  $2\pi$  (1 cycle/year).

**Figure 1** Annual amplitude and phase of thermoelastic deformation in Southwest China in the U, E, and N directions.

To more intuitively demonstrate the impact of bedrock thermal expansion on the consistency between GNSS and GRACE/GRACE-FO, this paper further compares the differences in the three parameters before and after thermal expansion correction of GNSS data. Since the results from CSR SH data and CSR mascon data are similar, the number and proportion of stations described below also use CSR SH data results as an example.

As can be seen from Figures 3a, 3b, and 3c, for the U direction, thermal expansion effects have a small impact on the consistency between the two datasets. Although most circles are concentrated near the red solid line, only the annual amplitude reduction rate of station YNLC is above it. The RMS reduction rate increased at 8 stations and the correlation coefficient increased at 9 stations, accounting for 3%, 21%, and 23% respectively, indicating that after thermal expansion correction, the consistency between GNSS deformation and GRACE/GRACE-FO deformation worsened at most stations, but the decrease was small.

As shown in Figures 3d, 3e, and 3f, for the E direction, thermal expansion correction brings some improvement to the consistency between the two datasets. Most station circles are above the red solid line. The numbers of stations with increased RMS reduction rate, annual amplitude reduction rate, and correlation coefficient are 38, 22, and 38, respectively, corresponding to proportions

of 97%, 56%, and 97%. This indicates that after thermal expansion correction, GNSS deformation at most stations becomes closer to GRACE/GRACE-FO deformation results, with improved consistency.

However, for the N direction, as shown in Figures 3g, 3h, and 3i, thermal expansion correction leads to a significant decrease in consistency between the two datasets. Most station points are below the red solid line and deviate significantly. All 39 stations show decreased RMS reduction rate and correlation coefficient, with only 10 stations showing increased annual amplitude reduction rate (26%). This indicates that after thermal expansion correction, the consistency between GNSS and GRACE/GRACE-FO results is significantly weakened. Whether before or after thermal expansion correction, the differences between GRACE/GRACE-FO SH products and mascon products (represented by blue and green respectively) are small, indicating good consistency between the two data products in describing surface deformation.

Note: a) to i) represent RMS reduction rate, annual amplitude reduction rate, and correlation coefficient of CSR SH and CSR mascon data relative to GNSS data in the U, E, and N directions. The horizontal axis represents parameter results before thermal expansion correction of GNSS data, while the vertical axis represents results after correction. Each circle represents results from one station. Blue and green circles represent results from CSR SH and CSR mascon data, respectively. The red line represents the reference line  $y = x$ . If a circle is above this line, it indicates that the consistency between GRACE/GRACE-FO data and GNSS data improves after thermal expansion correction, and vice versa.

**Figure 3** Comparison of three parameters in different directions before and after thermal expansion correction of GNSS data.

Table 2 shows changes in the three parameters representing consistency between deformation calculated by GRACE/GRACE-FO and GNSS deformation before and after thermal expansion correction. In the U direction, both CSR SH and CSR mascon products show slight decreases in RMS reduction rate and correlation coefficient, while annual amplitude reduction rate decreases by about 6%. Overall, CSR SH products show slightly better consistency with GNSS data in the U direction than CSR mascon products. In the E direction, CSR SH and CSR mascon products show increases in RMS reduction rate, annual amplitude reduction rate, and correlation coefficient, with improvements of about 2%, 6%, and 0.03, respectively. CSR mascon products show slightly better consistency with GNSS data than CSR SH products. In the N direction, the consistency between both CSR SH and CSR mascon products and GNSS deformation significantly worsens, with RMS reduction rate and correlation coefficient decreasing by about 3% and 0.2, respectively, while annual amplitude reduction rate decreases by more than 150%. The difference in consistency between CSR SH and CSR mascon data with GNSS data is small.

**Table 2** Comparison of average values of coefficients in U, E, N directions before

and after thermal expansion correction.

Direction	Thermal Expansion Correction	RMS	Annual Amplitude	Correlation
		Reduction Rate Average (%)	Reduction Rate Average (%)	Coefficient Average
U	Not Corrected	30.3	13.2	0.652
	Corrected	29.4	6.4	0.645
E	Not Corrected	18.0	-5.8	0.204
	Corrected	20.0	0.1	0.238
N	Not Corrected	22.5	17.4	0.457
	Corrected	12.9	-158.4	0.252

### 3.2 Impact of Bedrock Thermal Expansion on Analysis of Load Deformation Annual Signals

In this study area, surface load deformation and thermoelastic deformation mainly manifest as annual signals. Next, we will analyze the above results from the perspective of annual signals.

Table 3 shows that after thermal expansion correction at 39 observation stations, in the U direction, only station SCBZ shows a slight decrease in annual amplitude, while all other stations show decreased annual phase except for station XZCY. In the E direction, only 9 stations show decreased annual amplitude, while the rest show increased amplitude; 18 stations show decreased phase, while the rest show increased phase. In the N direction, only station XZCY shows increased annual amplitude, while all other stations show decreased amplitude; 15 stations show increased phase, while the rest show decreased phase. These results indicate that after thermal expansion correction of GNSS data, annual amplitude at most stations increases in the U direction while annual phase decreases; annual amplitude at most stations also slightly increases in the E direction, with phase changes varying by station; annual amplitude at most stations significantly decreases in the N direction, with phase decreasing at most stations. These results show that in small-scale regions, the annual amplitude of GNSS deformation after subtracting thermoelastic deformation does not necessarily decrease. This is because GNSS data contain multiple signals, and among non-tectonic signals, the phases of thermoelastic deformation caused by thermal expansion effects and load deformation may differ significantly, causing the superimposed deformation from the two factors to potentially become smaller. The differences in annual amplitude and phase between GNSS data before and after thermal expansion correction and GRACE/GRACE-FO results can be more intuitively compared through vectors.

Figure 4 [Figure 4: see original paper] shows in vector form the annual amplitude and phase of deformation in the U, E, and N directions obtained by fitting GRACE/GRACE-FO data and GNSS data at 39 GNSS stations in Southwest China. By comparing the magnitude and direction of GNSS/GNSS-Thermal and CSR SH/CSR mascon vectors, the impact of thermal expansion effects can be analyzed. From Figure 4a, the annual signal fitted from original GNSS data (red arrows) shows good spatial consistency in this region, meaning annual signals at adjacent stations do not change much. After thermal expansion correction (blue arrows), compared with original GNSS data results, thermal expansion effects have a small impact on annual signals (only minor differences between red and blue arrows), but still show systematic change patterns: the vector length at most stations slightly increases and rotates clockwise, meaning that after thermal expansion correction, annual amplitude at most stations in Southwest China increases in the U direction while annual phase decreases. CSR SH (green arrows) and CSR mascon (black arrows) annual amplitude and phase results are relatively close. Because CSR mascon undergoes data restoration and other processing, its annual amplitude is larger, with average values of 5.7 mm and 6.5 mm, respectively, but both are smaller than GNSS results with an average of 6.6 mm. This is because GRACE/GRACE-FO can only monitor factors of mass distribution changes, while GNSS also contains other signals. On the other hand, the average annual phase of GNSS is  $92.3^\circ$ , while CSR SH and CSR mascon phases are significantly larger, with averages of  $112.0^\circ$  and  $112.2^\circ$ , respectively, meaning deformation calculated from GRACE/GRACE-FO data reaches its peak later. After thermal expansion correction, the average annual amplitude and phase fitted from GNSS data are 7.1 mm and  $86.8^\circ$ , respectively, showing larger differences from GRACE/GRACE-FO results and thus worse consistency.

Figure 4b shows comparison results in the E direction. Compared with the U direction, the annual signal fitted from original GNSS data (red arrows) shows poor spatial consistency, meaning annual signals at some adjacent stations differ significantly, and annual amplitude is obviously smaller. After thermal expansion correction (blue arrows), compared with original GNSS data results, annual signals change little, showing no obvious systematic change patterns, with small and inconsistent changes in vector length and direction at different stations. The average annual amplitudes in the E direction obtained from CSR SH (green arrows) and CSR mascon (black arrows) are 0.4 mm and 0.5 mm, respectively, significantly smaller than the 1.0 mm from GNSS data. Unlike the U direction, phases in the E direction sometimes lag behind and sometimes lead GNSS, but overall, the average phases from the two GRACE/GRACE-FO datasets are  $43.6^\circ$  and  $42.2^\circ$ , respectively, while GNSS data show  $18.6^\circ$ , meaning the average time for deformation to reach its peak also lags behind GNSS. After thermal expansion correction, the average annual amplitude and phase from GNSS data are 1.1 mm and  $21.2^\circ$ , respectively, meaning the gap in annual amplitude with GRACE/GRACE-FO slightly increases, but annual phase becomes closer.

Figure 4c shows results in the N direction. Similar to the U direction, annual sig-

nals fitted from original GNSS data (red arrows) also show spatial consistency, meaning annual signals at adjacent stations are similar. However, after thermal expansion correction (blue arrows), compared with original GNSS data results, significant changes occur, showing systematic change patterns: annual amplitude obviously decreases, and phase also decreases at most stations. Similar to U and E directions, the average annual amplitudes calculated from CSR SH (green arrows) and CSR mascon (black arrows) are both 1.0 mm, significantly smaller than the 1.7 mm from original GNSS data. In terms of phase, both average values lag behind GNSS at  $95.1^\circ$  and  $95.5^\circ$ , respectively, while GNSS average phase is  $44.3^\circ$ . After thermal expansion correction, the average annual amplitude and phase fitted from GNSS data are 0.7 mm and  $30.9^\circ$ , respectively. Although the annual amplitude value is closer to GRACE/GRACE-FO, the gap in annual phase obviously increases.

The annual signal changes in the N direction are much more dramatic than in the U and E directions because temperatures are high in the Southern Hemisphere and low in the Northern Hemisphere in winter. Affected by the temperature gradient, north-south surface movement manifests as northward movement, so its phase is distributed around winter. GNSS stations in Southwest China are affected by local mass changes, and the phase of load deformation in the N direction is also around winter. Therefore, the superposition of the two factors makes the total deformation larger, and thermoelastic deformation in the N direction is relatively large in Southwest China, being the main factor in GNSS deformation. Thus, after subtracting thermal expansion effects, GNSS changes significantly.

Table 4 shows the average annual amplitude and phase of three-dimensional deformation time series at observation stations in the study area, including original GNSS deformation, bedrock thermoelastic deformation, GNSS deformation after thermal expansion correction, and deformation calculated from CSR SH and CSR mascon data. Table 4 shows that before thermal expansion correction of GNSS data, the annual amplitude of GNSS in the U direction is significantly larger than that of thermoelastic deformation, with the former's phase leading by about  $120^\circ$ . In the E direction, the annual amplitude of GNSS is also much larger than that of thermoelastic deformation, with the phases of the two differing by about  $190^\circ$  (nearly opposite). In the N direction, the difference in annual amplitude between GNSS and thermoelastic deformation is not large, and their phases are basically the same. After thermal expansion correction, the annual amplitude of GNSS in the U direction slightly increases, annual phase slightly decreases, and the difference from GRACE/GRACE-FO results also slightly increases. In the E direction, both annual amplitude and phase of GNSS slightly increase, but annual phase accuracy is poor, with the gap in annual amplitude with GRACE/GRACE-FO increasing, while annual phase becomes closer. In the N direction, both annual amplitude and phase of GNSS significantly decrease. Although the annual amplitude becomes closer to GRACE/GRACE-FO results, the gap in annual phase obviously increases.

**Table 4** Average annual amplitude and phase of deformation from different data.

Data Type	U Direction	E Direction	N Direction
	Amplitude (mm)	Phase (°)	Amplitude (mm)
	Amplitude (mm)	Phase (°)	Amplitude (mm)
GNSS (Original)	$6.6 \pm 0.7$	$92.3 \pm 8.3$	$1.0 \pm 0.4$
	$18.6 \pm 17.0$	$1.7 \pm 0.3$	$44.3 \pm 1.8$
	<i>Thermoelastic Deformation</i>		$0.8 \pm 0.2$

To study the impact of thermal expansion effects in detail, one representative station in each of the U, E, and N directions was selected for more in-depth analysis.

Figure 5a [Figure 5: see original paper] shows the deformation time series in the U direction at station SCSP. The annual amplitudes of the GNSS time series (black line) and thermoelastic deformation time series (green line) are 3.5 mm and 1.5 mm, respectively, with phases of  $59.6^\circ$  and  $224.1^\circ$ . The time series obtained by subtracting the two (cyan line) shows significantly increased annual amplitude of 5.0 mm and slightly decreased phase of  $55.0^\circ$ , which can also be observed in Figure 4a. The annual amplitudes fitted from CSR SH data (blue line) and CSR mascon data (red line) are 3.1 mm and 4.0 mm, respectively. It can be seen that the annual amplitude fitted from original GNSS data is smaller than CSR mascon results, while after thermal expansion correction, GNSS results become larger than both CSR SH and CSR mascon. Meanwhile, the annual amplitude reduction rate of CSR mascon relative to GNSS also changes from negative to positive. Additionally, the RMS reduction rates of both CSR SH and CSR mascon are improved, but correlation coefficients slightly decrease, indicating that after thermal expansion correction, the consistency between GNSS deformation and GRACE/GRACE-FO deformation depends on the type of GRACE/GRACE-FO data used and the comparison parameters selected. Therefore, these factors need to be considered when evaluating the impact of thermal expansion effects.

According to calculations by Wei et al., the peak of thermoelastic deformation in the U direction in the Northern Hemisphere occurs near summer, and Tan et al. calculated that the phase of thermoelastic deformation in mainland China is in July-August. For thermoelastic deformation in the U direction at stations in Southwest China, the average phase calculated in this study is  $216.3^\circ$ , consistent with their conclusions. However, Wei et al. found that load deformation in the Northern Hemisphere also peaks in summer, so the superimposed deformation of load and thermoelastic deformation is larger. Similarly, Tan et al. calculated that the average annual amplitude of superimposed GRACE and thermoelastic deformation in mainland China is larger than that calculated from GRACE alone by about 0.6 mm. However, the average phase of load deformation calculated from GRACE/GRACE-FO data in Southwest China in this study is about

112.0°, differing from the phase of thermoelastic deformation peak by about 104°. The combined deformation is smaller than the result from GRACE/GRACE-FO data alone, contradicting the conclusions of Wei and Tan. The main reason is that Southwest China, relative to the large-scale areas of the entire Northern Hemisphere and mainland China, is more affected by local factors. Notably, the cement monuments or metal rods used to install GNSS antennas are also affected by thermal expansion, causing vertical deformation. This study and those by Wei and Tan have not yet considered this effect. GNSS deformation contains both load deformation and thermoelastic deformation. Since U direction deformation in Southwest China is mainly affected by load deformation, after subtracting thermal expansion effects, the annual amplitude of GNSS deformation in the U direction in Southwest China actually increases while phase decreases, as can be observed in Figure 5a. This leads to decreased annual amplitude reduction rate, but considering that thermoelastic deformation is relatively small compared to U direction deformation, the overall impact is small, with only slight decreases in RMS reduction rate and correlation coefficient. These results indicate that thermal expansion effects have little impact on GNSS deformation results in the U direction in Southwest China, which is mainly affected by load deformation.

Figure 5b shows the deformation time series in the E direction at station SCNC. The annual amplitude and phase of the original GNSS time series (black line) are 0.4 mm and 5.1°, respectively, while those of the thermoelastic deformation time series (green line) are 0.3 mm and 209.2°, respectively. The phase difference between the two is large. After subtracting thermal expansion effects, the annual amplitude and phase of the GNSS deformation time series (cyan line) both increase, becoming 0.7 mm and 15.1°, respectively. The annual amplitudes from CSR SH (blue line) and CSR mascon (red line) data are both 0.4 mm, the same as the original GNSS data, with phases of 34.8° and 54.1°, respectively. Therefore, after thermal expansion correction, the annual amplitude of GNSS data is larger than GRACE/GRACE-FO results, and the annual phase is also closer. Although the annual amplitude reduction rate slightly decreases, the RMS reduction rate and correlation coefficient improve.

Figure 5c shows the deformation time series in the N direction at station LHAZ. Unlike the U and E directions, the annual amplitude and phase of GNSS (black line) and thermoelastic deformation (green line) are more similar, with annual amplitudes of 2.1 mm and 1.4 mm, respectively, and phases of 43.5° and 43.9°, respectively. After thermal expansion correction, the annual amplitude of GNSS data (cyan line) significantly decreases while annual phase slightly decreases, becoming 0.7 mm and 42.8°, respectively. The annual amplitudes of CSR SH (blue line) and CSR mascon (red line) are 1.3 mm and 1.5 mm, respectively, with annual phases of 87.4° and 81.3°, respectively. Therefore, the annual amplitudes of these two GRACE/GRACE-FO datasets are larger than GNSS results after thermal expansion correction, and the phase differences also become larger, causing the annual amplitude reduction rate, RMS reduction rate, and correlation coefficient of GRACE/GRACE-FO data relative to GNSS data to all

significantly decrease.

## 4 Summary and Outlook

Thermoelastic deformation is an important component of annual signals in surface deformation. Previous research has mainly focused on the vertical direction and used half-space thermoelastic deformation models. Based on the three-dimensional surface thermoelastic deformation theory in spherical space under geocenter-fixed constraints proposed by Fang et al., this paper quantitatively calculates the contribution of thermal expansion effects to three-dimensional surface deformation in Southwest China, a region with large annual surface deformation, and analyzes its impact on load deformation.

Thirty-nine CMONOC stations in Southwest China were selected to calculate and fit thermoelastic deformation time series at corresponding stations in the U, E, and N directions. The results show average annual amplitudes of 0.8 mm, 0.2 mm, and 1.2 mm, respectively, and average annual phases of 216.3°, 210.0°, and 45.1°, respectively. Meanwhile, fitting GNSS observation data in the U, E, and N directions yields average annual amplitudes of 6.6 mm, 1.0 mm, and 1.7 mm, respectively, and average annual phases of 92.3°, 18.6°, and 44.3°, respectively. It can be seen that in terms of annual amplitude, total GNSS deformation in the U and E directions is significantly larger than thermoelastic deformation, while in the N direction the difference is small. In terms of annual phase, the phase difference between total GNSS deformation and thermoelastic deformation is large in the U and E directions, while in the N direction the phases are relatively close.

Subtracting the corresponding thermoelastic deformation time series from GNSS time series and fitting again yields average annual amplitudes after thermal expansion correction of 7.1 mm, 1.1 mm, and 0.7 mm in the U, E, and N directions, respectively, and average annual phases of 86.8°, 21.2°, and 30.9°, respectively. The fitting results show that after subtracting thermoelastic deformation time series, annual amplitude slightly increases in the U and E directions, while amplitude significantly decreases in the N direction. Notably, the U direction results are inconsistent with previous studies, which showed that load deformation and thermoelastic deformation phases in the Northern Hemisphere are similar with superposition effects. However, this study shows large phase differences between the two in Southwest China. These conclusions indicate that thermal expansion effects and load effects may vary significantly in different regions, and special attention should be paid when analyzing the impact of thermal expansion effects on load deformation in different directions.

Furthermore, to evaluate the impact of thermal expansion effects, we calculated three parameters of load deformation time series calculated from CSR SH and CSR mascon data relative to GNSS deformation data before and after subtracting thermal expansion effects: RMS reduction rate, annual amplitude reduction rate, and correlation coefficient. After thermal expansion correction: (1) In the

U direction, the average values of CSR SH results decreased by 0.9%, 6.8%, and 0.007, respectively, while CSR mascon results decreased by 0.9%, 5.8%, and 0.006, respectively. (2) In the E direction, the average values of CSR SH results increased by 1.0%, 5.7%, and 0.034, respectively, while CSR mascon results increased by 0.9%, 7.5%, and 0.035, respectively. (3) In the N direction, the average values of CSR SH results decreased by 9.6%, 175.9%, and 0.205, respectively, while CSR mascon results decreased by 10.1%, 191.7%, and 0.203, respectively.

The comparison results of the three parameters show that after thermal expansion correction of GNSS deformation, the consistency between GRACE/GRACE-FO deformation and GNSS deformation slightly decreases in the U direction, improves to some extent in the E direction, but significantly weakens in the N direction. Two reasons cause this result: (1) Compared with the vertical direction, the annual signal in the horizontal direction is weak overall, with noise levels greater than the magnitude of thermal expansion effects, and the data itself may contain other geophysical signals (such as poroelastic deformation, tectonic movement, etc.). (2) The thermoelastic deformation model applied in this study is a global model, and its calculation accuracy in regions may be insufficient. Currently, there are no other effective theoretical models for quantitative comparison and verification of horizontal thermoelastic deformation calculated in this study, and its local accuracy needs further optimization. Additionally, this study ignores the thermal expansion effect of GNSS monuments, and its impact on vertical deformation will be discussed in future work.

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