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Monitoring and Mechanism Analysis of Glacier Mass Changes in the Pamir Plateau Based on Satellite Gravity

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Abstract: Glaciers are important indicators of climate change; however, the monitoring accuracy of glacier changes is not high, and the analysis of mechanisms is difficult to quantify. Based on GRACE time-varying gravity data and climate hydrological data from 2003 to 2022, this article conducts monitoring of glacier mass change in the Pamir Plateau and analyzes its impact mechanism. To improve monitoring accuracy, we propose a combined filtering method that combines Gaussian filtering, decorrelation filtering, and Fan filtering to reduce the spherical harmonic coefficient error of the GRACE gravity field model. Furthermore, we use forward modeling to recover the gravity field leakage signal and solve the signal attenuation problem caused by filtering and truncation in GRACE data processing. To quantify the response relationship between glacier mass changes and temperature and precipitation changes, we analyzed the cross-wavelet coherence between glacier mass changes and temperature and precipitation changes through wavelet transform, and calculated their resonance periods. Our research has found that the glacier mass in the Pamir Plateau has shown a significant downward trend in the past 20 years, with a rate of decrease of −0.54 cm/yr. As the main factors affecting glacier mass changes, both temperature and precipitation have a resonance period of 8–16 months with glacier mass changes. The results can provide decision support for scientific response to climate change in the Pamir Plateau and even globally.

Keywords: satellite gravimetry, Pamir, glacier mass, change monitoring

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1. Introduction

As the roof of the world located in the hinterland of the Eurasian continent, the Pamir Plateau is one of the most prevalent fields in geological, geographical, and climatic ecological research. The climate of the Pamir Plateau is arid, and precipitation mainly comes from the Indian Ocean monsoon airflow, with significant seasonal variations. The average altitude of the plateau is above 4500 m, and the glacier area exceeds 10,000 km^2. Glacier activity is intense and changes significantly. Glaciers, as an important water resource and indicator of global climate change, have significant impacts on regional ecological environments and global climate change [*Qin et al.*, 2021]. At present, research on glacier change in the Pamir Plateau is quite limited. Satellite remote sensing is expected to provide more convenient technical means for glacier monitoring [*Guan*, 2024].

With global warming, the melting of glaciers has increasingly significant impacts on regional water resources, ecological environment, and human society. Glacier mass changes have been increasingly recognized as the most important indicator of glacier reserve monitoring. However, due to the harsh geographical and climatic environment of the plateau, monitoring changes in glacier mass has always been a difficult problem

Review

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in the field of glacier monitoring. After the launch of the gravity satellite, the large-scale time-varying gravity field model based on satellite gravity observations provides a fast and efficient research method for monitoring glacier mass changes [*Chang et al.*, 2020].

Gardner et al. [2011] estimated the ice sheet mass changes of the Arctic Archipelago based on the GRACE monthly time-varying gravity field models from 2004 to 2009, and found that the glacier mass in the region continues to decline with an increasing rate [*Gardner et al.*, 2011]. The characteristic of this study is to use surface mass-budget modelling plus an estimate of ice discharge (SMB+D) and ICESat [*Zwally et al.*, 2002] independent observation to verify the reliability of GRACE results, and draw consistent conclusions. However, the limitation is that the duration of the study was too short (2007–2009) to determine long-term trends. *Rounce et al.* [2020] used an open-source Python glacier evolution model to predict glacier mass changes, estimating that the glacier mass loss in high mountain areas of Asia will reach 29–67 % from 2015 to the end of this century [*Rounce et al.*, 2020]. The innovation of this study lies in the glacier mass balance algorithm based on surface runoff observations [*Armstrong et al.*, 2019; *Immerzeel et al.*, 2010; *Zhang et al.*, 2019] and the Python glacier evolution model calibration based on Bayesian inference. The methods are innovative, but the research data is limited to ground observations, and the results are only rough quantitative estimates, without achieving accurate calculations. *Zhou et al.* [2021] used GRACE time-varying gravity field models to calculate the glacier mass changes in the Nyainqentanglha Range from 2002 to 2020, and found that the rate of change after conversion to equivalent elevation was −15.53 cm/yr. This study utilized GRACE satellite gravity observation data and precipitation [*Mohamed et al.*, 2019] and temperature [*Bjordal et al.*, 2020] model data, which had significant data advantages compared to the study by *Gardner et al.* [2011]. However, effective improvement measures were not proposed for the band errors in the GRACE model. *Wang et al.* [2021] used GRACE time-varying gravity data to study glacier mass changes in high-altitude regions of Asia. By introducing ICESat satellite laser altimetry data to improve the monitoring accuracy of glacier mass changes, they found that the glacier mass loss rate in the high-altitude regions of Asia was -28 ± 6 Gt/yr. The distinctive advantages of this study lie in the use of ICESat data to improve the precision and resolution of GRACE, as well as the validation of GRACE results, leading to consistent conclusions and confirming the reliability of glacier mass change monitoring technology based on GRACE. However, the DEM used in this study is SRTM data [*Farr et al.*, 2007] with 30-meter resolution, which is significantly lower in quality and accuracy compared to the ZY-3 2.5-meter resolution data used in our research. *Shi et al.* [2022] conducted research on the elevation changes of the Qinghai–Tibet Plateau using GRACE time-varying gravity data, GLDAS hydrological model, and GPS observation data. Their research feature is to analyze the coherence of three different results based on cross-wavelet transform [*Grinsted et al.*, 2004], and find that there are resonance signals between different results up to the year. However, the band errors in the GRACE model, like *Zhou et al.* [2021], have not been treated accordingly, which may have adverse effects on the monitoring results to a certain extent.

The above research shows the enormous potential and application prospects of satellite gravity in monitoring glacier mass changes. However, there are still a series of technical difficulties and data limitations in terms of the precision of satellite gravity field models, gravity field signal processing, fusion of satellite gravity data with satellite optical and laser altimetry data, hydrological, climatic, meteorological data, and monitoring duration. And there is also little further research on the mechanism of glacier mass changes.

This article intends to use GRACE time-varying gravity field to invert glacier mass changes in the Pamir Plateau. By combining filtering to improve the accuracy of satellite gravity field models and solving the problem of gravity field signal leakage during data processing through forward modeling, and so effective glacier mass change monitoring is expected to be achieved by satellite gravity and satellite remote sensing technology. Furthermore, a quantitative response relationship between glacier mass changes and climate and precipitation factors is expected to be constructed.

2. Materials and Methods

2.1. Research Data

The main data used in this article include time-varying gravity field data from gravity satellites, meteorological data, glacier cataloging data, and hydrological model data. The information of the above data is shown in Table 1.

Table 1. Research data information

No.	Data Type	Data Name	Time (year)	Resolution	Purpose
1	Time-varying gravity	GRACE/FO Gravity field series	2003–2022	1° × 1°	Glacier mass monitoring
2	Hydrological data	GLDAS	2003–2022	0.25°×0.25°	Surface water extraction
3	Meteorological data	ERA5	2003–2022	0.25°×0.25°	Analysis of temperature and precipitation
4	Glacier cataloging data	RGI	2000	–	Glacier boundary recognition

2.1.1. Satellite Gravity Data

The satellite gravity data used in this article are the CSR monthly time-varying gravity field models, with a maximum order of 60 and a time span of January 2003 to December 2022. The spatial resolution is about 500 km. The singular spectrum analysis method is used to interpolate and fill the data gap between GRACE and GRACE-FO satellites [*Yi and Sneeuw*, 2021]. As GRACE is not able to recover degree one Stokes coefficients in the Earth's mass center frame, the degree one Stokes coefficients are replaced by those derived by SLR data, to eliminate the impact of geocentric motion on glacier mass change monitoring [*Swenson et al.*, 2008]. To address the insensitivity of GRACE to C_{20} and the low accuracy of C_{30} due to GRACE accelerometer damage in October 2016, TN-13 and TN-14 data were used to replace C_{20} and C_{30}, respectively. In addition, Fan filtering and decorrelation filtering are used to reduce the impact of spatially correlated errors (stripes) and high-order noise, and the ICE6G-D model is used to correct for glacial isostatic adjustment [*Peltier et al.*, 2018].

2.1.2. Hydrological Data

The hydrological data used in this study comes from the Global Land Data Assimilation System (GLDAS) high-resolution hydrological model, which was generated by the Goddard Space Flight Center (GSFC) of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) using surface modeling and data assimilation techniques. GLDAS integrates multiple land surface models, supports hydrological analysis at both global and regional scales, and is highly compatible with GRACE satellite data. This article uses model data from the Noah land surface model, with a spatial resolution of 0.25°×0.25° and a temporal resolution consistent with GRACE time-varying gravity data.

2.1.3. Meteorological Data

The meteorological data used in this study is the fifth-generation reanalysis data (ERA5) released by the European Center for Medium Range Weather Forecasts (ECMWF), which is a reanalysis of climate and weather throughout the day. This data has a high spatiotemporal resolution, providing precipitation, temperature, wind, evaporation, and surface runoff data with a temporal resolution of 1 h and a spatial resolution of 0.25°×0.25° from 1950 to the present. Daily precipitation data can be obtained by summing up the data. This dataset assimilates a large amount of data from monitoring stations, especially in mountainous areas, where simulation results are closer to actual measurements and have higher accuracy [*Xie et al.*, 2021]. For example, rainfall data assimilates ground radar

observation data, and the ERA5 temperature in the Pamir and Qinghai–Tibet Plateau regions deviates less than 1.5 °C from the actual observation station temperature, which is significantly better than other meteorological data. This article uses ERA5 model data with a time span from January 2003 to December 2022.

2.1.4. Glacier Cataloging Data

The glacier catalogue data used in this article is the latest RGI 7.0 Global Glacier Profile Complete Catalogue released by GLIMS on September 19, 2023 [*RGI Consortium*, 2017]. This catalogue is mainly based on remote sensing images from 1999 to 2021, supplemented by SPOT-5, Terra and other data materials. Compared with previous versions, this version has higher quality because it has fixed glacier cataloging problems caused by seasonal snowfall, glacier debris, geographic location, and contour artifacts. In addition, it also provides common boundary and glacier centerline data for individual glaciers.

2.2. Methods

2.2.1. Satellite Gravity Field Signal Filtering

Due to the influence of onboard sensor errors, satellite attitude errors, and orbit errors, the mass changes inverted by GRACE contain a large amount of north-south strip errors and high-frequency noise, which affect the effective signal [*Chang et al.*, 2024]. The reason for the strip errors is the strong high-order correlation in GRACE spherical harmonic coefficients [*Swenson and Wahr*, 2006]. According to the correlation between surface mass changes and the order of spherical harmonics, when the error is greater than the effective signal, it will lead to an imbalance in signal-to-noise ratio, and appropriate filtering is needed to reduce the impact of north-south errors.

Due to the presence of both correlation errors and high-frequency errors in the spherical harmonic coefficients of the GRACE gravity field model, it is difficult to effectively eliminate errors using a single filtering method. Based on the analysis of error characteristics, this study proposes a combined filtering method that combines Gaussian filtering with decorrelation filtering and Fan filtering to maximize the elimination of spherical harmonic coefficient errors in the GRACE gravity field models.

Gaussian filtering is not affected by real signals, but uses Gaussian smoothing kernel function to reduce the weight of high-order terms in spherical harmonics, thereby reducing the error of high-order terms. Gaussian filtering can effectively reduce high-order term errors and weaken the influence of stripe errors to a certain extent, but it is difficult to eliminate the correlation errors between spherical harmonics in space [*Swenson and Wahr*, 2006]. When the degree is the same and the order reaches a certain value, there is a certain correlation between odd and even orders. For this correlation error, this article uses decorrelation filtering to further eliminate it. When the order is less than n, it is considered that there is no correlation error in the spherical harmonic coefficient and no filtering processing is performed. When the order is greater than n, perform m-order polynomial fitting on odd and even orders of the spherical harmonic coefficients with a sliding window of l, and remove the fitting value as the correlation error from the spherical harmonic coefficients. For the north-south strip errors caused by the same order and degree of spherical harmonic coefficients, anisotropic Gaussian filtering and Fan filtering are used to further eliminate them by processing coefficients of different orders and degrees.

We take the inversion of global water storage changes in 2003 as an example to verify the effectiveness of the proposed combined filtering method. Without any processing, there is a significant north-south band error, and after filtering with P3M8, the impact of the error is weakened to some extent, but there is still a significant band error in the middle and low latitudes. Comparing different filtering results, it is found that using 300 km Fan filtering yields better results than Gaussian filtering, with a more significant effect in removing high-frequency errors. The combination of Gaussian filtering and Fan filtering with decorrelation filtering further weakens the error, especially in the vicinity of the equator where the weakening effect is better (Figure 1).

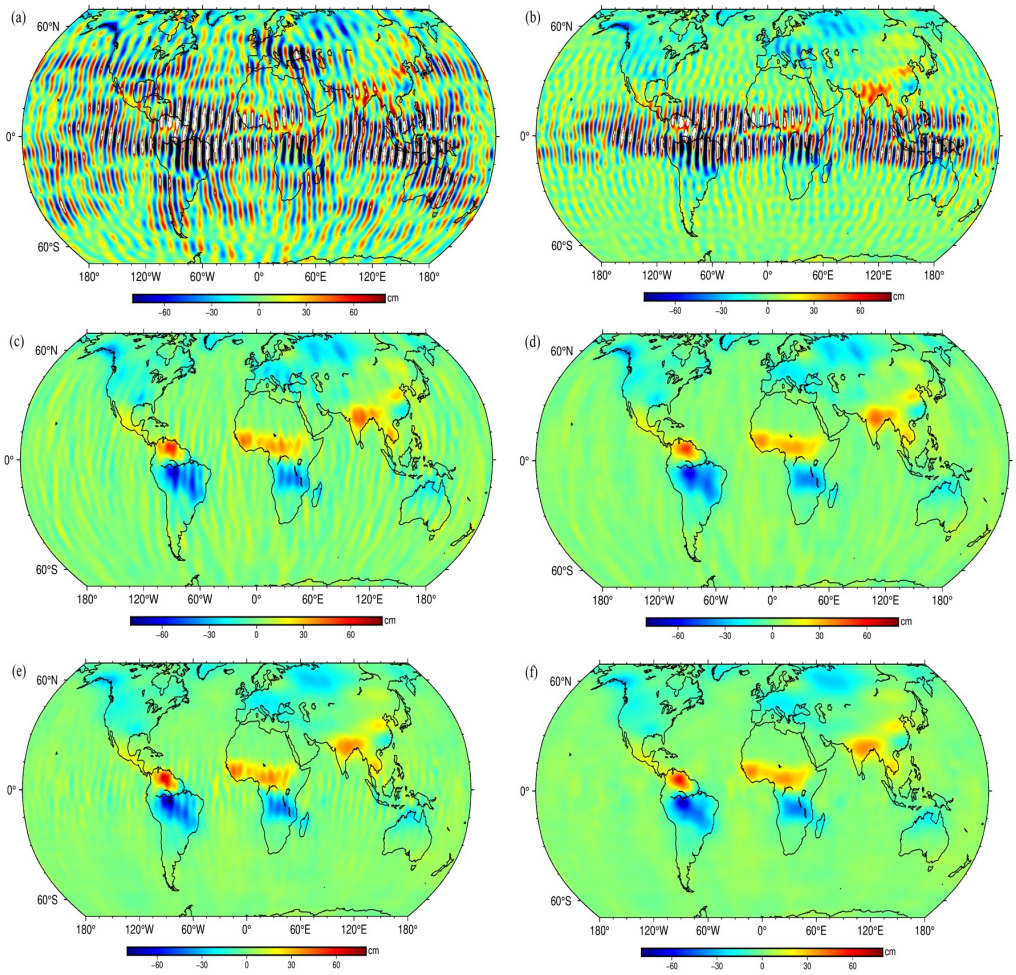


Figure 1. Comparison of spatial filtering effects: (a) no filtering; (b) decorrelation filtering; (c) Gaussian filtering; (d) Fan filtering; (e) Gaussian filtering with decorrelation filtering; (f) Fan filtering with decorrelation filtering.

2.2.2. Correction of Satellite Gravity Signal Leakage Error

To reduce error propagation, the spherical harmonic coefficients are usually truncated to a certain order when using GRACE to invert changes in surface mass. However, both high-order coefficient truncation and filtering will cause the gravity field signal to diffuse and leak outward, resulting in deviation from the true value. To improve monitoring accuracy, this article uses forward modeling method [*Chen et al.*, 2009] to recover leaked signals and solve the problem of signal attenuation caused by filtering and truncation in GRACE data processing. This method adjusts the difference between the simulated signal and the observed value through multiple iterations, and compares it with a set threshold. When the difference is less than the threshold, the simulated signal is considered as the result of leakage signal recovery. The specific steps are as follows:

1. Let the mass change after filtering be M_1;
2. Set $M_0 = M_1$ as the initial estimate, then apply the same filtering to M_0 and M_1 to obtain the result M_2;
3. Calculate the difference c between M_1 and M_2, determine whether it meets the set threshold, if not, let $M_0 = M_0 + \Delta$, iterate the above steps until the difference meets the set threshold.

This method is more effective for areas where local signal changes caused by glacier mass changes are significant, and the restored spatial location of mass changes is closer to

its true location, which can effectively avoid the insufficient spatial resolution of gravity field models.

2.2.3. Calculation of Glacier Mass Change

The land water storage changes in GRACE time-varying gravity inversion mainly include surface runoff, groundwater, soil water, and snow water equivalents [*Strassberg et al.*, 2009]. Due to the extremely high altitude, cold and dry climate, only sparse vegetation develops in the Pamir Plateau. And the barrier of permafrost layers throughout the year, results in minimal changes in groundwater. Therefore, the influence of groundwater and vegetation canopy water changes can be ignored when calculating glacier mass changes. Because the surface runoff in the research area is mainly composed of meltwater from ice and snow, and the continuous inflow and outflow maintain a relatively balanced state, the impact of runoff on land water storage can also be ignored. Therefore, in the study, only the equivalent changes in soil water and snow water should be considered to estimate the glacier mass changes.

The main way to obtain soil water and snow water equivalents in this study comes from the GLDAS hydrological model. Compared with the CPC hydrological model and WGHM hydrological model, the GLDAS hydrological model has higher accuracy and better performance due to its ability to drive multiple surface models that are not coupled with the atmosphere and integrate a large amount of observational data [*Rzepecka et al.*, 2016]. This article uses the GLDAS hydrological model to extract four layers of soil water and snow water equivalents that are consistent with the GRACE data time span (January 2003 to December 2022), and then performs spherical harmonic expansion on the extracted soil water and snow water equivalents, and truncates the spherical harmonic order to 60. Next, after deducting the average value during the research period, perform the same filtering process as GRACE data. Finally, the surface water storage is calculated for extracting glacier mass changes. According to the principle of water balance, the glacier mass change can be expressed as:

$$\Delta ICE = \Delta TWS - \Delta SM - \Delta SWE \quad (1)$$

where ΔTWS represents the land water storage change, ΔSM represents the soil water change, and ΔSWE represents the change in snow water equivalent, where ΔTWS is calculated from GRACE time-varying gravity data, and both ΔSM and ΔSWE are extracted from the hydrological model after deducting the average value of the study period.

3. Results and Discussion

3.1. Mass Changes in Pamir Glaciers

3.1.1. Overall Changes of Water Storage

According to calculation above, we have obtained the time series of total water storage and surface water storage in the Pamir Plateau from 2003 to 2022 (Figure 2). The missing data caused by orbit adjustment and the alternation of GRACE and GRACE-FO are filled by SSA interpolation. In Figure 2, the red sequence represents the total water storage changes inverted by GRACE, and the blue represents the surface water storage changes extracted from GLDAS. Overall, both show a downward trend with obvious cyclical characteristics, with the GLDAS time series showing a relatively weak downward trend and overall stability, indicating that the surface water storage in the Pamir Plateau has maintained a basic balance for a long time. We further used least squares fitting to quantitatively estimate the long-term trend of total water storage, and obtained that the change rate of total water storage during the study period was −0.75 cm/yr, with an annual amplitude of 5.01 cm, while that of surface water was −0.22 cm/yr, with an annual amplitude of 3.13 cm. In addition, there are significant differences between GRACE and GLDAS results in 2015 and 2022, possibly due to the impact of strong earthquakes during the same period, although there were no obvious anomalies in precipitation and evapotranspiration during the same period.

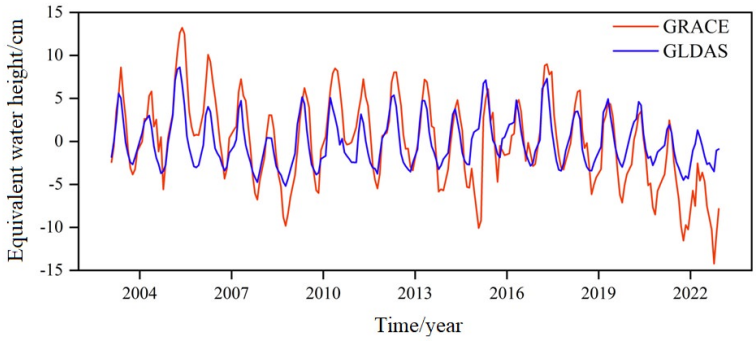


Figure 2. Changes in total water storage and surface water storage.

To further investigate the water storage changes, we used least squares fitting to analyze the spatial distribution of the change rate and amplitude of the total water storage and surface water storage (Figures 3 and 4). According to Figure 3, both the total water storage and surface water storage in the Pamir Plateau show a decreasing trend, and the spatial distribution of their deceleration is consistent. However, the change rate of −1.24 cm/yr in the western part of the total water storage is significantly faster than that of −0.53 cm/yr in the eastern part, while the difference in surface water storage changes between the eastern and western parts is relatively small. According to Figure 4, the change amplitude of total water storage and surface water storage in the Pamir Plateau is larger in the west and smaller in the east, but the change amplitude of total water storage is significantly greater than that of surface water storage.

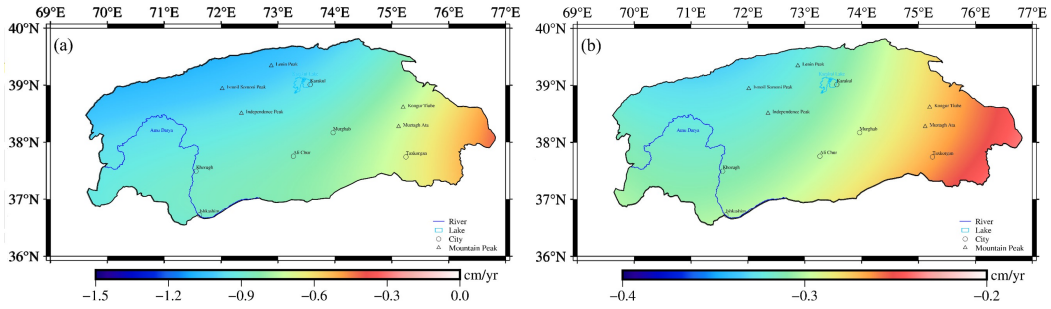


Figure 3. Rate of total water storage change: (a) total water; (b) surface water.

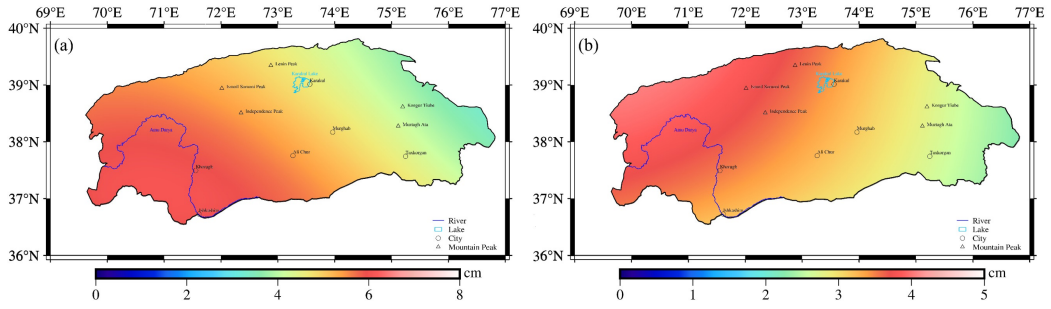


Figure 4. Amplitude of water storage change: (a) total water; (b) surface water.

This study utilizes the comprehensive advantages of GRACE and GLDAS data to monitor water storage changes. GLDAS data has a higher resolution, which can reveal more localized regional changes, while GRACE scale is larger, which can reveal more comprehensive overall changes. The integration of two types of data is not only beneficial for complementing monitoring accuracy and resolution, but also a necessary means of calculating glacier mass changes.

3.1.2. Glacier Mass Changes

After using satellite gravity to obtain the total water storage changes, we calculated the glacier mass change time series of the Pamir Plateau from 2003 to 2022 (Figure 5, where the black and red time series represent the results without and after leakage error correction, respectively). According to Figure 5, the glacier mass changes show a significant downward trend, accompanied by obvious periodic variations. After leakage error correction, the glacier mass change rate was −0.54 cm/yr, indicating that the overall trend of glacier mass change in the Pamir Plateau during the study period was melting, which is consistent with the global warming environmental change trend. In addition, comparing the results of Figure 2 and Figure 5, it can be found that in the past 20 years, the total water storage, surface water storage, and glacier mass of the Pamir Plateau have all shown a downward trend, but the decline rate of glacier mass is much greater than that of surface water.

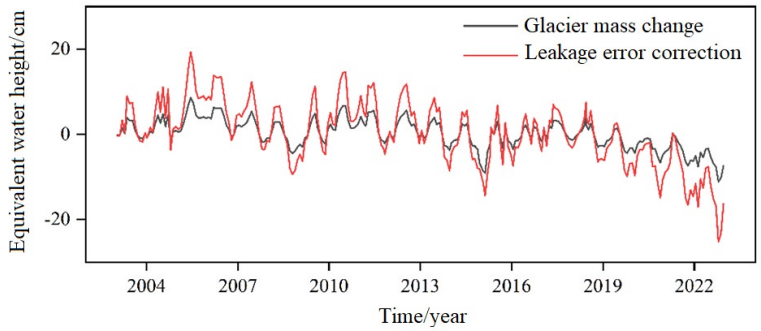


Figure 5. Changes in glacier mass on the Pamir Plateau.

To further analyze the spatial distribution of glacier mass changes, we used least squares fitting to obtain the rate and annual amplitude of glacier mass changes (Figures 6 and 7). According to Figures 6 and 7, the rate and amplitude of glacier mass change are both severe in the west and mild in the east, which is consistent with the spatial distribution of surface water in Figures 3 and 4.

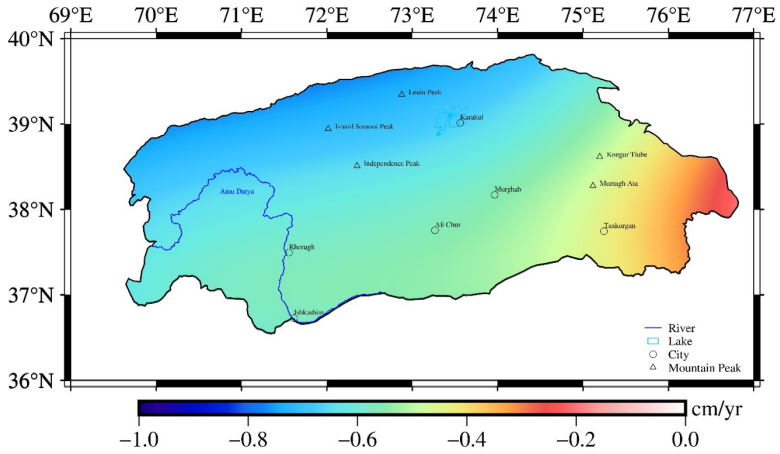


Figure 6. Rate of glacier mass change.

The essential reason for the significant differences in the changes and amplitudes of total water volume and glacier reserves in the Pamir Plateau between the east and west part is the differences in terrain, resulting in differences in water vapor transport channels, climate, and population distribution. The West Pamir is an area of typical high mountain and deep valley. On the one hand, it is influenced by the westerlies, and when water vapor from the Atlantic travels eastward along the mountain channel, it encounters a sharp rise in high mountain terrain, resulting in increased precipitation, lowered snow lines, and widespread glaciers. On the other hand, deep valleys serve as good drainage channels and

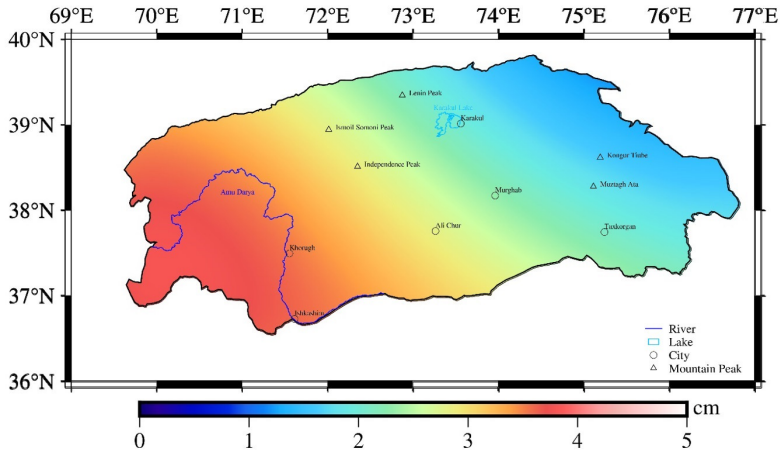


Figure 7. Amplitude of glacier mass change.

provide relatively warm, humid conditions suitable for irrigation and settlement; these characteristics make them powerful factors that aggravate changes and amplify variations in total water volume and glacier reserves Although the terrain of the East Pamir is high, it is open and flat, with a dry climate, high snow lines, sparse population and vegetation. These are the main reasons for the low changes and amplitudes in total water volume and glacier reserves.

3.2. Reliability Analysis and Verification of Glacier Mass Change Monitoring Results

The monitoring errors of satellite gravity mainly stem from GRACE gravity field model and GLDAS hydrological model. The GRACE CSR monthly scale spherical harmonic gravity field model (RL06) has a spatial resolution of approximately 300–500 km, corresponding to a geoid precision of 1–2 cm. After grid processing, its Mascon grid model has a spatial resolution of approximately 100 km in the mid latitude region of the Pamir Plateau, corresponding to a geoid precision of 10–20 cm. The GLDAS hydrological model generated by GSFC and NOAA using surface modeling and data assimilation techniques integrates multiple land surface models, supports global and regional scale hydrological analysis, and is highly compatible with GRACE satellite data. The Noah land surface model data used in this study has a spatial resolution of $0.25° \times 0.25°$ and a spatial resolution of approximately 20 km in the mid latitude region of the Pamir Plateau. The temporal resolution is consistent with GRACE time-varying gravity data. The fifth-generation reanalysis data ERA5 released by ECMWF is a reanalysis data of climate and weather throughout the day, including precipitation, temperature, wind evaporation, and surface runoff. The data has a time resolution of 1 h and a spatial resolution of $0.25° \times 0.25°$.

This research is based on the above data to monitor the glacier mass change and analyze the change mechanism. The biggest advantage of satellite gravity data is its monthly time resolution and centimeter level precision, but its significant drawback is its spatial resolution of only about 100 km, and with the increase of resolution, the corresponding precision rapidly decreases. But compared to the area of 100,000 km^2 of the Pamir Plateau, this resolution is still effective. Moreover, the fusion of GLDAS hydrological models with higher precision and temporal and spatial resolution, as well as ERA5 climate and meteorological data, can result in significant downscaling effects. Just like *Dussaillant et al.* [2025], who achieved the fusion of aerospace remote sensing data with on-site observation data through time downscaling, and used statistical modeling, interpolation, and extrapolation to achieve long-term monitoring of global glacier mass changes, we effectively integrated satellite gravity, satellite altimetry, satellite optics, as well as hydrological, climate, and meteorological data through downscaling, forming a high-quality dataset for glacier mass change monitoring and mechanism analysis, providing a prerequisite for improving the reliability of research results.

In terms of reliability verification, it is difficult to achieve comprehensive independent verification of monitoring accuracy using field observation data or satellite altimetry data, because satellite gravity monitors the overall glacier mass changes of the plateau. The reliability of monitoring results can only be verified within a local area and a specific period. To conduct this study, we used ICESat-2 ATL08 data for validation and ZY-3 optical stereo images to generate high-precision DEM to monitor the glacier elevation changes at Outer-Alay Range glacier area of the Pamir Plateau from 2018 to 2022. The distribution of ICESat data used is shown as Figure 8, the generated DEM is shown in Figure 9, and the glacier elevation changes are shown in Figure 10. According to Figure 10, the glacier elevation of Outer Alay Range showed a significant downward trend from 2018 to 2022, especially in the easternmost part where the changes were most pronounced. This is consistent with the satellite monitoring results of the overall trend of changes in the plateau.

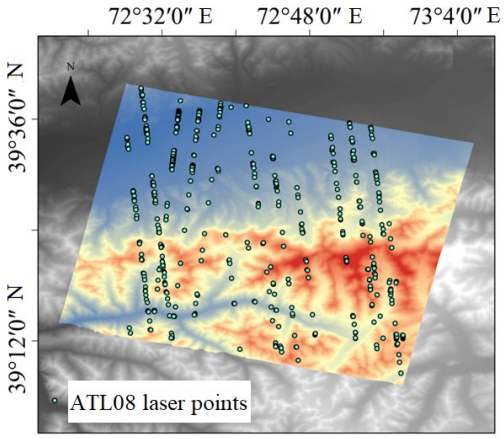


Figure 8. Spatial distribution of ATL08 laser points at Outer Alay Range.

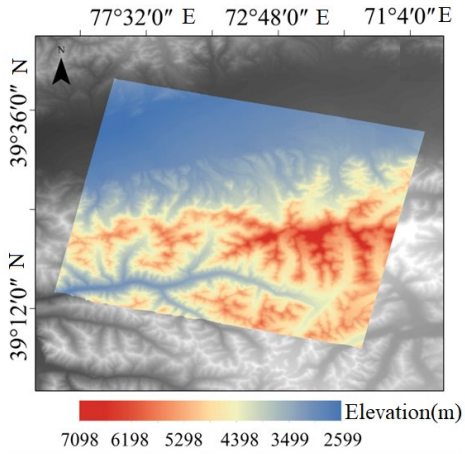


Figure 9. DEM extraction results at Outer Alay Range.

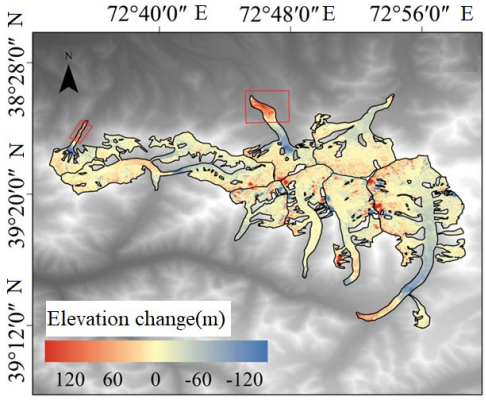


Figure 10. Glacier surface elevation changes at Outer Alay Range.

3.3. Analysis of Glacier Mass Change Mechanisms

3.3.1. Temporal and Spatial Variations of Temperature and Precipitation

Climate, especially temperature and precipitation, are the most direct factors driving glacier changes [*Toropov et al.*, 2017]. According to ERA5 data, we calculated the time series of average precipitation and average temperature changes from 2000 to 2022 (Figures 11 and 12). Precipitation shows a downward trend with a change rate of −6 mm/yr, while temperature shows a weak upward trend. The decrease in precipitation and the increase in

temperature are the fundamental and inevitable factors for the continuous reduction of glacier mass.

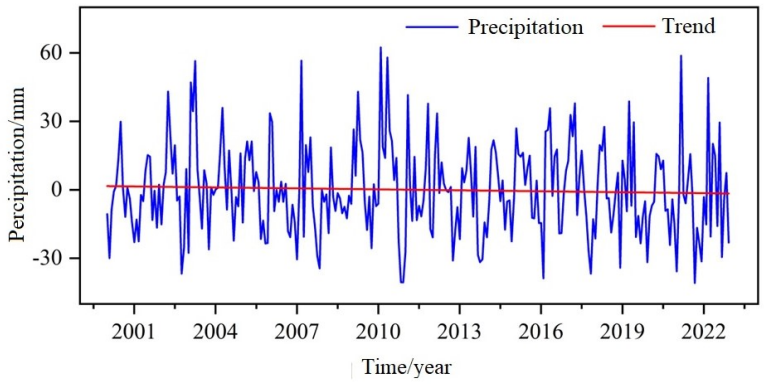


Figure 11. Average precipitation change.

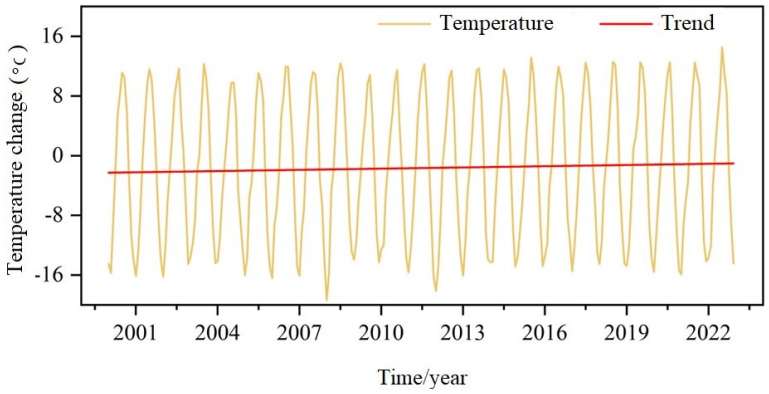


Figure 12. Average temperature change.

We analyze temperature and precipitation separately based on the melting period (April–September of each year) and the accumulation period (October–March of the following year). Figures 13 and 14 show the spatial distribution of average temperature and precipitation during the accumulation and melting periods, respectively. According to Figures 13 and 14, during the accumulation and melting periods, the temperature is higher on the east and west sides of the plateau, while the temperature is lower in the middle. During the accumulation period, precipitation is more abundant in the west and less in the east, while during the melting period, it is less in the middle and more on the east and west sides.

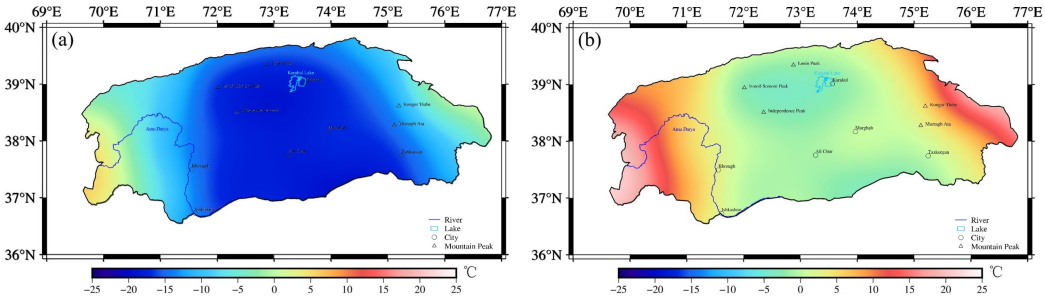


Figure 13. Average temperature spatial distribution: (a) accumulation period; (b) melting period.

Based on spatiotemporal analysis, we calculated the changes of monthly average rainfall, total water storage, surface water storage, and glacier mass in the Pamir Plateau

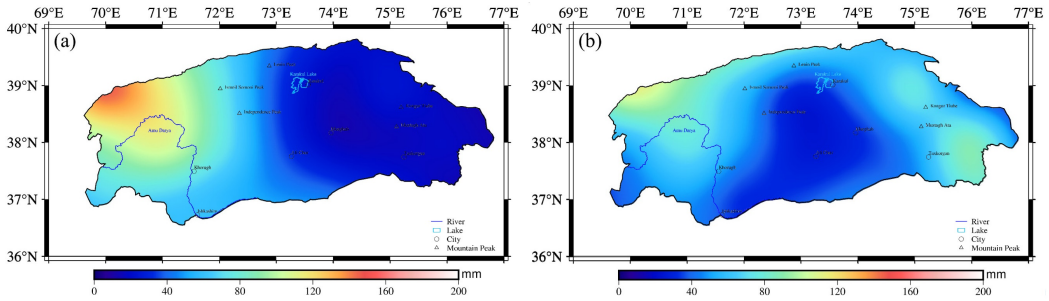


Figure 14. Average precipitation spatial distribution: (a) accumulation period; (b) melting period.

(Figure 15). According to Figure 15, precipitation reaches its maximum in March, surface water storage reaches its annual peak in April, and the annual maximum glacier mass occurs in May. The delay in surface water storage relative to precipitation is about one month, while precipitation has a two-month delay relative to glacier mass accumulation, mainly due to the impact of temperature changes.

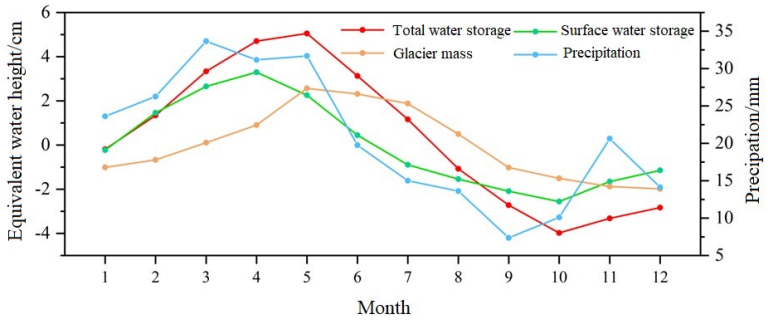


Figure 15. Changes in water storage and precipitation in different months.

3.3.2. The Response Relationship Between Glacier Mass Changes and Temperature and Precipitation

In order to further investigate the response relationship between glacier mass changes and temperature and precipitation, we used cross-wavelet transform to reveal the common oscillation period of two time series before and after, and further utilized cross-wavelet coherence for periodic analysis. This can not only determine the consistency of their changes, but also analyze their phase relationship in the time-frequency domain. By taking temperature and precipitation as the front sequence and glacier mass change as the back sequence, we can obtain the cross-wavelet energy spectrum and wavelet coherence spectrum analysis results between glacier mass change and temperature and precipitation (Figures 16 and 17). In Figures 16 and 17, the black thin solid lines represent the cone of influence of wavelet boundary effect, and the thick black solid lines represent the red noise test with a confidence level of 95 % (i.e., the correlation between the two is significant). ← indicates a negative correlation between two sequences, → indicates a phase change (i.e., a positive correlation between the two), ↓ indicates a 90° lead change in the previous sequence, and ↑ indicates a 90° lag change in the sequence.

According to Figure 16, there is a resonance period of 8–16 months between glacier mass and temperature changes, and it has passed the significance test. During this period, majority of the black arrows point to the right, indicating that the trends of the two are consistent, that is, they are in phase in the annual cycle. Wavelet coherence analysis compensates for the shortcomings of cross-wavelet transform in low-energy regions and can be used to measure the local correlation degree between the two in the time-frequency domain. Analysis shows that in addition to resonance period of 8–16 months, there are

also dispersed resonance periods, such as the 6-month resonance period in 2010–2012 and a 2.7-year resonance period in 2017–2022.

Figure 17 shows that there is a resonance period of 8–16 months between glacier mass and precipitation changes, while its 64-month resonance period signal is relatively weak and did not pass the significance test. During the resonance period, majority of the black arrows have a rightward component, indicating that the two have the same change trend. At the same time, there is an upward component, indicating a slight lag in glacier changes relative to precipitation changes, with a lag period of 1–2 months for precipitation. The wavelet coherence between glacier mass and precipitation changes shows that there is also a resonance period of more than 30 months between glacier mass and precipitation changes.

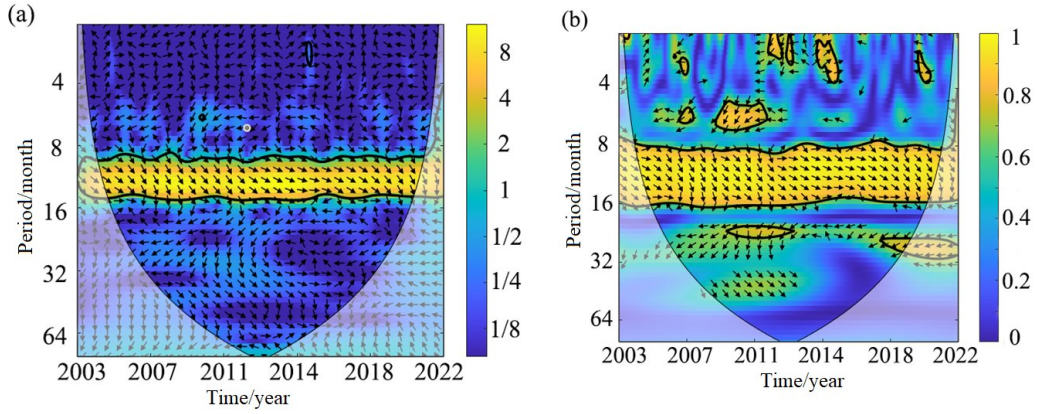


Figure 16. Glacier mass and temperature changes cross-wavelet and wavelet coherence power spectra.

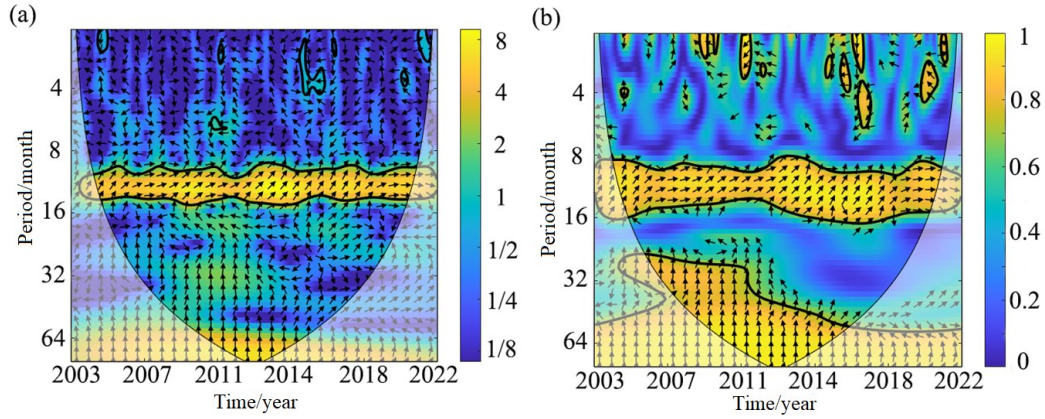


Figure 17. Glacier mass and precipitation change cross-wavelet and wavelet coherence power spectra.

The main cycle of temperature and precipitation changes is 12 months, and the comprehensive response cycle of glacier mass changes to temperature and precipitation is also 12 months. In theory, the resonance period between glacier mass and changes in temperature and precipitation should be a full-time resonance. The inability to achieve full time resonance lies in the delay of glacier mass changes in temperature and precipitation. The rise in temperature leads to a lag of 2 months in the accumulation of glacier mass with precipitation, which is a phase delay of 1/6 cycle. As a result, glaciers cannot resonate with temperature and precipitation within 1/3 cycle, i.e., 4 months, and can only resonate within 8 months per year. When two consecutive annual resonance cycles occur, it is manifested as a 16-month resonance cycle.

4. Conclusions

The Pamir Plateau is the roof of the world, and so monitoring glacier changes in the Pamir Plateau is not only helpful for ecological environment protection and water resource management in the region, but also of great significance for a deeper understanding of global climate change. Satellite gravity provides a new technological means for monitoring glacier changes. Based on GRACE time-varying gravity data and combined with climate and hydrological data, this article conducts monitoring of glacier mass changes in the Pamir Plateau (from 2003 to 2022) and studies the response relationship between glacier mass changes and their main influencing factors, temperature and precipitation. Research has found that the glacier mass in the Pamir Plateau has shown a significant downward trend in the past 20 years, with a rate of decrease of −0.54 cm/yr. The main factors affecting glacier mass changes are temperature and precipitation, and the resonance period between glacier mass changes and temperature and precipitation is 8–16 months.

At the technical level, this study first uses a combination of Gaussian filtering, decorrelation filtering, and Fan filtering to eliminate the spherical harmonic coefficient error of the GRACE gravity field model. Then, the gravity field leakage signal is restored through forward modeling to solve the signal attenuation problem caused by filtering and truncation during GRACE data processing. Finally, cross-wavelet transform and cross-wavelet coherence were used to conduct periodic analysis of glacier mass changes and temperature and precipitation anomalies, revealing the response relationship between glacier mass changes and temperature and precipitation.

The innovative technologies developed in this study can provide valuable application references for monitoring glacier mass changes in other regions all over the world. The monitoring results of glacier mass changes can provide data and technical support for glacier protection and water resource management in the Pamir Plateau.

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References

Armstrong R. L., Rittger K., Brodzik M. J., et al. Runoff from glacier ice and seasonal snow in High Asia: separating melt water sources in river flow // Regional Environmental Change. — 2019. — Vol. 19, no. 5. — P. 1249–1261. — https://doi.org/10.1007/s10113-018-1429-0

Bjordal J., Storelvmo T., Alterskjær K., et al. Equilibrium climate sensitivity above 5∘C plausible due to state-dependent cloud feedback // Nature Geoscience. — 2020. — Vol. 13, no. 11. — P. 718–721. — https://doi.org/10.1038/s41561-020-00649-1

Chang X. T., Zhu G. B., Liu W., et al. High-resolution satellite gravimetry method and key technology. — Beijing : Geological Publishing House, 2020. — (In Chinese).

Chang X. T., Zhu G. B., Qu Q. L., et al. Research and demonstration application of key technologies for gravity satellites. — Beijing : Geological Publishing House, 2024. — P. 16–21. — (In Chinese).

Chen J. L., Wilson C. R., Tapley B. D., et al. 2005 drought event in the Amazon River basin as measured by GRACE and estimated by climate models // Journal of Geophysical Research: Solid Earth. — 2009. — Vol. 114, B5. — https://doi.org/10.1029/2008jb006056

Dussaillant I., Hugonnet R., Huss M., et al. Annual mass change of the world's glaciers from 1976 to 2024 by temporal downscaling of satellite data with in situ observations // Earth System Science Data. — 2025. — Vol. 17, no. 5. — P. 1977–2006. — https://doi.org/10.5194/essd-17-1977-2025

Farr T. G., Rosen P. A., Caro E., et al. The Shuttle Radar Topography Mission // Reviews of Geophysics. — 2007. — Vol. 45, no. 2. — https://doi.org/10.1029/2005rg000183

Gardner A. S., Moholdt G., Wouters B., et al. Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago // Nature. — 2011. — Vol. 473, no. 7347. — P. 357–360. — https://doi.org/10.1038/nature10089
Grinsted A., Moore J. C. and Jevrejeva S. Application of the cross wavelet transform and wavelet coherence to geophysical time series // Nonlinear Processes in Geophysics. — 2004. — Vol. 11, no. 5/6. — P. 561–566. — https://doi.org/10.5194/npg-11-561-2004
Guan W. J. Distribution and characteristics of surge-type glaciers in High Mountain Asia : PhD thesis / Guan W. J. — Lanzhou : Lanzhou University, 2024. — https://doi.org/10.27204/d.cnki.glzhu.2024.000034
Immerzeel W. W., Beek L. P. H. van and Bierkens M. F. P. Climate Change Will Affect the Asian Water Towers // Science. — 2010. — Vol. 328, no. 5984. — P. 1382–1385. — https://doi.org/10.1126/science.1183188
Mohamed A. A., Pavlovskii I., Cey E. E., et al. Effects of preferential flow on snowmelt partitioning and groundwater recharge in frozen soils // Hydrology and Earth System Sciences. — 2019. — Vol. 23, no. 12. — P. 5017–5031. — https://doi.org/10.5194/hess-23-5017-2019
Peltier W. R., Argus D. F. and Drummond R. Comment on "An Assessment of the ICE-6G_C (VM5a) Glacial Isostatic Adjustment Model" by Purcell et al. // Journal of Geophysical Research: Solid Earth. — 2018. — Vol. 123, no. 2. — P. 2019–2028. — https://doi.org/10.1002/2016jb013844
Qin D. H., Yao T. D., Ding Y. J., et al. Introduction to Cryospheric Science. — Beijing : Springer Singapore, 2021. — https://doi.org/10.1007/978-981-16-6425-0
RGI Consortium. Randolph Glacier Inventory – A Dataset of Global Glacier Outlines, Version 6. — 2017. — https://doi.org/10.7265/4M1F-GD79
Rounce D. R., Hock R. and Shean D. E. Glacier Mass Change in High Mountain Asia Through 2100 Using the Open-Source Python Glacier Evolution Model (PyGEM) // Frontiers in Earth Science. — 2020. — Vol. 7, no. 331. — https://doi.org/10.3389/feart.2019.00331
Rzepecka Z., Birylo M. and Nastula J. Evaluation of the global land data assimilation system (GLDAS) data products essential for determination groundwater in Poland // International Multidisciplinary Scientific GeoConference: SGEM. — Sofia : STEF92 Technology Ltd., 2016. — P. 313–320. — https://doi.org/10.5593/SGEM2016/B31/S12.041
Shi T., Guo J., Yan H., et al. Assessing Height Variations in Qinghai-Tibet Plateau from Time-Varying Gravity Data and Hydrological Model // Remote Sensing. — 2022. — Vol. 14, no. 19. — P. 4707. — https://doi.org/10.3390/rs14194707
Strassberg G., Scanlon B. R. and Chambers D. Evaluation of groundwater storage monitoring with the GRACE satellite: Case study of the High Plains aquifer, central United States // Water Resources Research. — 2009. — Vol. 45, no. 5. — https://doi.org/10.1029/2008wr006892
Swenson S., Chambers D. and Wahr J. Estimating geocenter variations from a combination of GRACE and ocean model output // Journal of Geophysical Research: Solid Earth. — 2008. — Vol. 113, B8. — B08410. — https://doi.org/10.1029/2007jb005338
Swenson S. and Wahr J. Post-processing removal of correlated errors in GRACE data // Geophysical Research Letters. — 2006. — Vol. 33, no. 8. — P. L08402. — https://doi.org/10.1029/2005gl025285
Toropov P. A., Shestakova A. A. and Smirnov A. M. Methodological aspects of heat balance components estimation on mountain glaciers // Russian Journal of Earth Sciences. — 2017. — Vol. 17, no. 4. — E. — https://doi.org/10.2205/2017es000605
Wang Q., Yi Sh. and Sun W. Continuous Estimates of Glacier Mass Balance in High Mountain Asia Based on ICESat-1,2 and GRACE/GRACE Follow-On Data // Geophysical Research Letters. — 2021. — Vol. 48, no. 2. — e2020gl090954. — https://doi.org/10.1029/2020gl090954
Xie S. F., Wang Y. J., Huang L. K., et al. Accuracy analysis of Tm calculated by ERA5 and MERRA-2 reanalysis data over China // Journal of Geodesy and Geodynamics. — 2021. — Vol. 41. — P. 771–776. — (In Chinese).
Yi Sh. and Sneeuw N. Filling the Data Gaps Within GRACE Missions Using Singular Spectrum Analysis // Journal of Geophysical Research: Solid Earth. — 2021. — Vol. 126, no. 5. — e2020JB021227. — https://doi.org/10.1029/2020jb021227
Zhang F., Thapa S., Immerzeel W., et al. Water availability on the Third Pole: A review // Water Security. — 2019. — Vol. 7. — P. 100033. — https://doi.org/10.1016/j.wasec.2019.100033
Zhou M., Chang X. T., Zhu G. B., et al. Analysis of glacier changes in the Nyainqentanglha Mountain based on the combination of satellite gravity and optical remote sensing // Acta Geodaetica et Cartographica Sinica. — 2021. — Vol. 50, no. 10. — P. 1331–1337. — https://doi.org/10.11947/j.agcs.2021.20200463 — (In Chinese).
Zwally H. J., Schutz B., Abdalati W., et al. ICESat's laser measurements of polar ice, atmosphere, ocean, and land // Journal of Geodynamics. — 2002. — Vol. 34, no. 3/4. — P. 405–445. — https://doi.org/10.1016/s0264-3707(02)00042-x