Characteristics and mechanism of lake water changes in the Tianshan region during 2002-2022

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Abstract

The variations in the lake water storage in the Tianshan region are an important indicator of climate change and play a key role in understanding the hydrological mass balance. Based on altimetry and satellite gravity, we investigated the spatiotemporal characteristics of the lake water storage changes during 2002–2022, and examined the contributions and proportions of all of the hydrological components to the mass balance. The results indicate that the total water storage of the lake complex showed an increasing rate (0.73 ± 0.10 Gt/a). We found two abrupt wet periods in 2010 and 2016 (the regional total mass increased by 65.73 Gt and 67.35 Gt, respectively), which were reflected not only by the lake water storage but also by the soil moisture, snow water, and even GNSS displacement fields. Compared with their contributions to the mass (22% and 14%), the variations in lake area were remarkably slight (0.01% and 0.014%). Among the hydrological components, the soil moisture played a dominant role, and the contribution of the snow accumulation changes was also considerable. The mass anomalies were closely related to the precipitation caused by the increase of water vapor content, which was further associated with the occurrence of ENSO events (r=0.55, p<0.01). The results revealed that the long-term trend of the GNSS vertical displacements exhibited a better stability after the load correction was applied, which could reflect the long-term ground deformation more accurately. This study contributes to our understanding of the complex hydrological and tectonic processes in the Tianshan region.

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1	Characteristics and mechanism of lake water changes in the
2	Tianshan region during 2002–2022
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8	indicator of climate change and play a key role in understanding the hydrological mass balance.
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26 Plain Language Summary: Tianshan lake water storage variations are vital for climate change 27 assessment and hydrological balance. Using altimetry and satellite gravity during 2002–2022, we 28 studied Tianshan Lake storage changes. Total lake water storage showed an increasing trend of 29 0.73±0.10 Gt/a. Two wet periods occurred in 2010 and 2016, impacting not only lake storage but 30 also soil moisture, snow water, and GNSS displacement fields. Regional mass increased by 65.73 Gt and 67.35 Gt. Lake area changes were minor (0.01% and 0.014%) but contributed significantly 31 32 (22% and 14%) to mass. Soil moisture dominated among hydrological components, and snow 33 accumulation changes were noticeable. Mass anomalies correlated closely with precipitation, 34 linked to El Niño-Southern Oscillation events (r=0.55, p<0.01). Intensified El Niño led to 35 increased Tianshan water vapor and precipitation. We calculated elastic vertical displacements 36 from mass changes and corrected GNSS data. Long-term vertical displacements showed better 37 stability after correction. This study enhances our knowledge of complex hydrological and 38 tectonic processes in Tianshan.

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40 Key Points
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41 (1) The lake water storage increased, and two anomalous periods occurred, as verified in other42 hydrological components

43 (2) The ENSO-related precipitation anomaly was the main cause of the two anomalous mass

44 periods in the Tianshan region

45 (3) Load deformation correction is of great importance for maintaining the long-term stability of46 the GNSS displacement field

47 1 Introduction

48	As an essential reservoir of surface water on Earth, lakes are highly sensitive to climate
49	change, and their water storage variations are considered to be indicators of climate change
50	(Adrian et al., 2009; Zhang et al., 2019; Woolway et al., 2020). There are a large number of lakes
51	distributed globally, and approximately 53% of the large lakes, especially those located within
52	continents, experienced a continuous decrease in water storage from 1992 to 2020 (Yao et al.,
53	2023). Research findings clearly demonstrate that the fluctuations in lake water storage primarily
54	stem from natural factors, including precipitation (Zhang et al., 2017; Wang et al., 2022a) and
55	evaporation (Zhao et al., 2022), as well as human activities (Grant et al., 2021). Therefore,
56	monitoring the dynamic changes in lake water storage is crucial for understanding the global water
57	cycle and its driving factors (Xu et al., 2022b). Additionally, lakes are a significant component of
58	regional water storage, and accurate monitoring and estimation of their mass changes contribute to
59	a better understanding of the regional mass balance.

The Tianshan region is situated in the arid and semi-arid zone within the interior of the Eurasian continent and has a typical temperate continental climate. It is influenced by three monsoon belts, namely the southwest, Indian, and northwestern monsoons, but is primarily influenced by the northwestern monsoon. The main sources of the water storage in the lake complex in the Tianshan region are generally believed to be precipitation and glacial meltwater. The study area encompasses the entire Tianshan mountain range and its surrounding regions. In 66 this study, we focused on the region enclosed by the black dashed line in Figure 1. Although this 67 region includes numerous lakes of different sizes, for the sake of convenience, we selected eight 68 representative large lakes, namely Balkhash, Kapchagay, Issykkul, Sasykkol, Alakol, Saysan, 69 Ulungur, and Bosten (labeled with numbers in Figure 1), which occupied an area of ~35,000 km². 70 These lakes contribute significantly to the total water storage of the lake complex. The study area 71 consists of the Tianshan snow-covered area and the lake complex, which encompasses the 72 hydrological variations within the region. This study area selection facilitated the comprehensive 73 analysis of the high mountain snowmelt, lake water level changes, and their relationships with 74 meteorological factors.

75





78 Balkhash, 2 - Kapchagay, 3 - Issykkul, 4 - Sasykkol, 5 - Alakol, 6 - Zaysan, 7 - Ulungur, 8 - Bosten. The green dots

80

76

81 The Tianshan region in China contains a considerable number of lakes, forming a relatively

⁷⁹ denote the locations of GPS stations.

82	concentrated lake complex. This area serves as a typical region for studying lake level and/or
83	water storage variations. Research has revealed that extreme precipitation events in the Tianshan
84	region are closely related to the Indian Ocean summer monsoon (Zhong et al., 2017) and abnormal
85	westerly winds (Yi et al., 2016). Zhang et al. (2023) pointed out that the main sources of water of
86	the lakes located at middle and low elevations in the Tianshan region are precipitation and glacial
87	meltwater, while the lakes at high elevations are primarily replenished by glacial meltwater.
88	Therefore, the lake water storage changes in the Tianshan region are directly associated with ice
89	and snow melting caused by climate variations in the region. Additionally, lakes located in densely
90	populated areas are more susceptible to the influence of human activities (Li et al., 2003).
91	Currently, research on the lakes in the Tianshan region has mainly focused on long-term
92	monitoring of lake water levels and surface areas. Yi et al. (2016) studied the water level changes
93	in the lake complex in the Tianshan region and identified a mass anomaly period in 2010. They
94	attribute this anomaly to the dominant influence of the northwestern monsoon. Liu et al. (2019)
95	utilized moderate resolution imaging spectroradiometer (MODIS) 500 m resolution global water
96	body data to study the interannual and seasonal variations in the surface areas of 14 lakes in
97	Central Asia from 2001 to 2016, as well as the influencing factors. Their results revealed that the
98	lakes located in plain areas experienced a reduction in surface area, while the high mountain lakes
99	exhibited expansion. Zhang et al. (2022a) used multisource satellite data to investigate the water
100	level changes in Lake Issyk-Kul from 1958 to 2020. Their results indicate that before 1998,
101	human activities were the main cause of the continuous decline in the water level. However, after
102	2000, the increases in rainfall and glacial meltwater, as well as the decrease in water usage, led to
103	short-term recovery of the lake's water level. The above studies indicate that there is significant

interannual variability in the water volume of the lakes in the Tianshan region. Investigating this
can help us understand and explain the characteristics of climate change and human activities in
the Tianshan region.

107 The main observational parameters reflecting lake water storage changes are the lake water 108 level and lake surface area, both of which can be obtained through remote sensing techniques and 109 in situ water level measurements. In situ water level monitoring is the traditional method for 110 monitoring the water levels of reservoirs and lakes, but it can be affected by complex terrain 111 conditions and incomplete data recording. In addition, in situ water level measurements cannot cover inland lakes located in remote and inaccessible regions, resulting in a lack of long-term and 112 113 effective water level change data. With the emergence of remote sensing measurement techniques, 114 represented by altimetry satellites, many researchers have opted to use these methods instead of 115 traditional water level monitoring approaches due to their regular data acquisition periods and 116 wide data coverage range (Jiang et al., 2017). Remote sensing measurements, which offer 117 advantages such as all-weather capability, comprehensive coverage, and high efficiency, have 118 been widely employed in lake hydrological research. Currently, there are two main types of 119 measurement methods: geometric measurements and physical measurements. Geometric 120 measurements refer to the use of optical imagery combined with spatial geodetic measurement 121 techniques to obtain changes in the lake surface area. For instance, researchers use optical remote 122 sensing data such as Landsat data to monitor global surface water area changes (Yao et al., 2019) 123 or regional surface water area changes (Olthof et al., 2015; Zhang et al., 2017; Xu et al., 2021). 124 They then utilize altimetry techniques to monitor changes in the lake levels (Zhang et al., 2011; 125 Zhang et al., 2019; Xu et al., 2022), thereby obtaining the variations in the lake water storage.

Physical measurement methods refer to direct detection the mass changes of lake water storage
using gravity detection satellites, such as the Gravity Recovery and Climate Experiment (GRACE)
(Xu et al., 2020), as well as the gravity changes generated by variations in reservoirs (Yi et al.,
2017; Tangdamrongsub et al., 2019). The results obtained from both geometric and physical
measurements can mutually corroborate each other.

131 In addition to a lake complex, the Tianshan region contains continuously melting glaciers and 132 snow, which are significant contributors to the lake water storage variations (Yi et al., 2016). The 133 lake variations in the Tianshan region are closely linked to the water contributions from glacier 134 and snow melt (Wang et al., 2013; Rinzin et al., 2023). Therefore, studying the changes in glaciers 135 and snow enables us to gain a deeper understanding of the mechanisms behind lake variations. 136 Regarding glacier monitoring, because glaciers are located in high-altitude areas, there are limited 137 results from in situ observations, which can lead to deviations. Therefore, global and regional 138 glacier monitoring mainly relies on the following types of satellite remote sensing observation 139 methods: high-resolution digital elevation model (DEM) differencing (Gardelle et al., 2012; 140 Gardelle et al., 2013), estimating glacier thickness changes using altimetry satellites (Kääb et al., 141 2012; Kääb et al., 2015; Wang et al., 2017a), and directly obtaining mass changes using gravity 142 satellites such as GRACE (Matsuo and Heki, 2010; Jacob et al., 2012; Yi and Sun, 2014). 143 Additionally, changes in the snowline have been used to infer glacier variations (Barandun et al., 144 2021). Due to observational limitations, many researchers have primarily focused on studying the 145 long-term trends of glaciers. For instance, Hugonnet et al. (2021) provided the longest time span 146 for global glacier melting rates, and reported annual global glacier melting of 267 ± 16 Gt. At the 147 regional scale, Wang et al. (2017b) and Wang and Sun (2022b) reported continuous annual glacier elevation changes in the Asian high mountain regions, while Barandun et al. (2021) reported annual glacier mass balance results for the Tianshan region from 1999 to 2017. With the development of satellite technology, obtaining glacier mass changes with a higher time resolution will become possible.

152 Furthermore, the lakes in the Tianshan region exhibit significant mass fluctuations, and 153 together with other hydrological components such as soil moisture and groundwater, they impose 154 a substantial load effect on surface deformation observations in this region. This phenomenon is 155 included in global navigation satellite system (GNSS) observations (Heki, 2004; Heki and Arief, 156 2021; White et al., 2022). This interferes with our ability to extract the signals of long-term 157 tectonic motions. To study tectonic movements effectively, it is essential to accurately account for the effects of these surface loads (Rao and Sun, 2022). Pan et al. (2019) utilized global positioning 158 159 system (GPS) and GRACE data to obtain the three-dimensional deformation field in the Tianshan 160 region. Pan et al. (2021) presented the most comprehensive distribution of the vertical 161 displacement field in mainland China, corrected the vertical displacement due to surface loads 162 using GRACE data, and subsequently obtained information about tectonic movements. Wu et al. 163 (2022) also combined levelling measurements and GNSS data to obtain high-precision vertical 164 displacement data for the Tibetan Plateau region. Wen et al. (2023) constructed a global mass 165 change model and used Green's function integration method to calculate the vertical displacement 166 due to surface loads in mainland China. They found that the GNSS vertical velocity field in the 167 Tianshan region is primarily driven by extensive glacier melt-induced surface mass changes, 168 which result in rapid uplift of Earth's surface.

169

The above-mentioned research indicates that currently, researchers have mainly utilized

170	multisource space geodetic techniques to study the glacier mass balance in the Tianshan region
171	(Farinotti et al., 2015; Brun et al., 2017; Barandun et al., 2021) or have conducted studies from the
172	perspective of tectonic movements to investigate the three-dimensional deformation and orogenic
173	motion in the Tianshan region (Li et al., 2022; Pan et al., 2023). However, the spatiotemporal
174	distribution characteristics of the lake water storage changes in the Tianshan region are not yet
175	well understood. Questions related to the hydrological components contributing to water storage
176	changes in the lake complex, their relationship with changes in the precipitation in the region, the
177	total mass balance of the region, and the main physical mechanisms driving water storage changes
178	in the lake complex are all significant scientific questions that warrant attention.

179 Therefore, the goal of this study was to utilize multisource remote sensing observation data, 180 including altimetry and GRACE data, to investigate the spatiotemporal distribution of the water 181 storage changes in the lake complex in the Tianshan region from 2002 to 2022. Additionally, 182 GNSS displacement observations were employed to investigate the characteristics of the surface 183 load deformation. The goals were to quantify and analyze the lake water changes during two 184 anomalous periods, to quantitatively calculate the contributions of the lake water, soil moisture, 185 snow water, glacial mass changes, and other hydrological components to the total surface mass 186 change monitored by GRACE and finally to explore and analyze the physical mechanisms 187 underlying the two occurrences of abnormal mass changes.

188 2 Datasets and methods

189 2.1 Datasets

190 2.1.1 Global surface water area dataset

191	To build a g	lobal mass re	edistribution model a	nd calculate the	e load deformation,	as well as to
192	extract the releva	ant lake wate	r area, in this study,	we used a glob	al surface water are	ea dataset that
193	includes statistic	al data on the	e location, extent, and	l temporal distr	ibution of the surfa	ce water from
194	1984 to 2020 (J	ean-Francois	et al., 2016). This	dataset was ge	nerated using 4,45	3,989 images
195	acquired by Land	dsat-5, 7, and	1 8 satellites from Ma	arch 16, 1984,	to December 31, 20	021, and each
196	pixel was classif	ied as water	or non-water using a	n expert syster	n. The data produc	ts are divided
197	into two categor	es: monthly	variations during the	entire period a	and temporal chang	es during two
198	separate periods	(1984–1999	and 2000–2020). T	'he dataset con	tains 442 images,	one for each
199	month from Mar	ch 1984 to D	ecember 2021. In thi	s study, we obt	ained the lake area	changes from
200	2002 to 2020 usi	ng the Goog	le Earth Engine (GEI	E) and fitted the	e water level–area r	elationship of
201	altimetry data to	estimate the	water volume change	es of the lake co	omplex from 2002 to	o 2022.
202	2.1.2 Altimetry d	ata				
203	Most of the	lakes in the	study area are cove	red by altimetr	y data, and the wa	ter level data
204	products	were	obtained	from	several	websites

205 (https://ipad.fas.usda.gov/cropexplorer/global reservoir/, https://dahiti.dgfi.tum.de/en/map/, 206 http://hydrolare.net/catalogue.php). Multiple sources of altimetry satellite data were used, 207 including data from European remote sensing satellite (ERS)-1, Geosat follow-on (GFO), ERS-2, 208 JASON-1, ENVISAT, and others. For all of the lakes, remote sensing was utilized to obtain the 209 lake area changes, and the water level data obtained through altimetry were combined to construct 210 the lake-water level area curve. After data screening and outlier removal of the products from 211 different organizations and systematic error adjustment, we obtained water level monitoring data 212 for all of the lakes in the study area. The basic information about the lake complex is presented in

No.	Lake	longitude (°E)	latitude (°N)	Level Method	Water type
1.00		iongicular (12)			water type
1	Balkhash	75.81	46.64	Altimetry	Lake
2	Kapchagay	77.63	43.80	Altimetry	Lake/reservoir
3	Issykku	77.3	42.4	Altimetry	Lake
4	Sasykkol	80.97	46.59	Altimetry	Lake
5	Alakol	81.75	46.14	Altimetry	Lake
6	Zaysan	83.88	48.02	Altimetry	Lake/reservoir
7	Ulungur	87.32	47.28	Altimetry	Lake
8	Bosten	87.05	42	Altimetry	Lake

215 2.1.3 GNSS data

216 To analyze the ground deformation characteristics in the Tianshan region, in this study, we 217 utilized GNSS data from the Nevada Geodetic Laboratory 218 (http://geodesy.unr.edu/NGLStationPages/GlobalStationList), which are in the IGS2008 reference 219 frame. Due to various factors such as receiver malfunctions and changes in the surface 220 environment during GPS operations, long-term GPS stations may experience data gaps. To 221 address this issue, the TSAnalyzer software was employed to remove anomalies and outliers from 222 the GNSS time-series data (Wu et al., 2018).

223 2.1.4 Precipitation data

Precipitation data were one of the key datasets used in this study. We adopted the Global Precipitation Climatology Centre (GPCC) model. The GPCC was established in 1989 in response to the World Meteorological Organization's (WMO) request and is operated by the German Meteorological Service (Deutscher Wetterdienst). The center's mission is to analyze and establish 228 a global rainfall database based on observed rainfall data for daily and monthly precipitation at the 229 Earth's surface. It is the world's largest precipitation database. All GPCC products are based on 230 observed global land surface gridded precipitation datasets, which use a large number of station 231 observations to compute the grid values. Several reanalysis datasets have been compared, and it 232 has been reported that the GPCC precipitation model is better suited for long-term precipitation 233 change studies in Central Asia (Hu et al., 2018). In this study, we utilized the GPCC-generated 234 monthly precipitation dataset with a spatial resolution of $1^{\circ} \times 1^{\circ}$ from 1982 to the present 235 (Schneider et al., 2014).

236 2.1.5 GRACE data

237 To calculate the mass balance in the study area and compare it with lake water storage 238 changes and to investigate the contributions of the various hydrological components, in this study, 239 we utilized the GRACE mascon products for 2002 to 2021 released by the Center for Space 240 Research (CSR), Jet Propulsion Laboratory (JPL), and Goddard Space Flight Center (GSFC). The 241 GRACE satellite, launched in 2002, provides monthly gravity signals resulting from surface mass 242 redistribution, offering unprecedented spatiotemporal observation data for studying Earth's mass 243 redistribution (Wahr et al., 1998; Tapley et al., 2019). The GRACE mascon data from the three 244 institutions has been subjected to preprocessing, including the addition of degree one (Swenson et 245 al., 2008) and replacement of the C20 and C30 coefficients using satellite laser ranging-based 246 estimates (Cheng et al., 2011; Loomis et al., 2020). Additionally, to account for post-glacial 247 rebound signals, all of the mascon products use ICE6G-D to correct for the impact of glacial 248 isostatic adjustment (GIA) (Peltier et al., 2018). The GRACE mascon products require no further 249 preprocessing and can be directly applied in hydrological, oceanographic, and cryospheric studies

within watersheds. Furthermore, the JPL's mascon product provides scale factors for recovering
real surface signals. To address the missing months in the GRACE data and the 11-month data gap
between the GRACE and GRACE-FO satellites, in this study, we employed singular spectrum
analysis (SSA) to conduct data interpolation (Yi and Sneeuw, 2021).

254 2.1.6 Wind field data and atmospheric water vapor data

255 To study the physical mechanisms of the lake water level changes, in this study, we utilized 256 the vertical wind field data ERA5 provided by the European Centre for Medium-Range Weather 257 Forecasts (ECMWF). ERA5 is the fifth-generation reanalysis of global climate and weather data 258 for the past 80 years, from 2002 to 2022, with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ (Hersbach et al., 259 2023). The atmospheric water vapor content data are based on the measurements from the ozone 260 monitoring instrument (OMI) from January 2005 to December 2020, providing a monthly 261 averaged total column water vapor (TCWV) dataset with a resolution of 1°×1° (Borger et al., 262 2021).

263 2.1.7 Other hydrological models

The Tianshan region contains complex hydrological components, including soil moisture, snow water, and groundwater. Therefore, land hydrological models are essential auxiliary data for studying the mass balance in the Tianshan region. The Global Land Data Assimilation System (GLDAS) is a widely used hydrological model that provides high-precision global surface land data and has been extensively used in weather and climate forecasting, water resources applications, and hydrological investigations (Bai et al., 2016; Deng and Chen, 2017). In this study, GLDAS was employed to obtain the changes in the soil moisture in the Tianshan region. 271 Additionally, the snow water equivalent product provided by the ECMWF was utilized to simulate

- 272 the changes in the snow water in the Tianshan region. Furthermore, the WaterGAP hydrological
- model was employed to assess the changes in the groundwater (Müller et al., 2021).

274 2.2 Methods

- 275 2.2.1 Mass recovery and load vertical deformation
- To obtain the time-varying gravity field information from GRACE, based on the theory proposed by Wahr et al. (1998) and using the time-variable gravity spherical harmonic coefficients ΔC_l^m and ΔS_l^m , it is possible to estimate the density anomaly at a certain point on the Earth's surface in terms of the equivalent water height:

$$\Delta EWH(\phi,\theta) = \frac{a\rho_e}{3\rho_W} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \bar{P}_l^m(\cos\phi) \left(\frac{2l+1}{1+k_l}\right) [\Delta S_l^m \sin(m\theta) + \Delta C_l^m \cos(m\theta)], \qquad (1)$$

where ΔEWH is the mass change expressed as the equivalent water height, \overline{P}_l^m is the normalized associated Legendre polynomial, *a* is the Earth's radius, and ρ_e and ρ_W are the densities of the Earth and water, respectively. h_l , l_l , and k_l are the load Love numbers. Equation (1) is the fundamental equation used to calculate surface mass changes from GRACE time-variable gravity and express them in terms of the equivalent water height.

285 The vertical displacement of the surface mass change, Δh , can be calculated using the 286 following formula (Fu and Freymueller, 2012):

$$\Delta h(\phi,\theta) = a \sum_{l=1}^{\infty} \sum_{m=0}^{l} \bar{P}_{l}^{m}(\cos\phi)(\frac{h_{l}}{1+k_{l}})[\Delta S_{l}^{m}\sin(m\theta) + \Delta C_{l}^{m}\cos(m\theta)].$$
(2)

287 It should be noted that due to the certain orbital altitude of gravity satellites, the gravity field

288 signal attenuates with increasing altitude, making it difficult for GRACE to observe higher-degree 289 gravity field components. Therefore, the time-variable gravity products have to be truncated at 290 lower degree. The GRACE data has a spherical harmonic coefficient truncation at 60°, and the 291 summation term in Equation (2) is limited to 60°. As a result, Equation (2) cannot be used to 292 calculate the full-spectrum load displacement field. Furthermore, the GRACE time-variable 293 gravity signal includes not only surface hydrological mass changes but also the influences of non-294 hydrological (tectonic) signals (Rao and Sun, 2022). When calculating the load deformation, the 295 non-hydrological signals need to be removed. Therefore, the vertical displacement caused by the 296 surface mass change Δm at the calculation point can be calculated using the following formula 297 (Farrell, 1972; Erikson and MacMillan, 2014):

$$U_{h} = \iint \Delta m(\theta', \varphi') G_{R}(\alpha) \cos\varphi' d\theta' d\varphi', \qquad (3)$$

where α is the angular distance between the load point and the load source, and $G_R(\alpha)$ is the vertical displacement Green's function, which is typically based on the preliminary reference Earth model (PREM) (Farrell, 1972).

301 2.2.2 Estimation of lake water storage changes

To calculate the changes in the lake water volume over a period of time, in this paper, altimetry data are utilized to obtain the lake water surface elevations and remote sensing data are utilized to obtain the lake surface areas. Furthermore, following the method proposed by Taube (2000), we can estimate the changes in the lake water volume:

$$\Delta V = \frac{1}{3} (L_2 - L_1) \times (S_1 + S_2 + \sqrt{S_1 S_2}), \tag{4}$$

306 where ΔV is the change in the lake water volume (km^3) , L_1 and L_2 are the water levels in two

307 consecutive time periods, and S_1 and S_2 are the corresponding areas. Calculating the lake water 308 storage change typically involves computing the difference between two consecutive time periods.

309 2.2.3 Analysis of time series

To investigate the periodic variations in the Tianshan region, Fourier transformation was utilized to analyze the periodic spectral characteristics of the various mass components. Subsequently, a least-squares method is applied to fit the time series and obtain the long-term trend and periodic components. The specific fitting method can be expressed as follows:

$$f(t) = a + bt + \sum_{i} A_{i} \cos\left(\frac{2\pi}{T_{i}}(t - \varphi_{i})\right) + \varepsilon,$$
(5)

314 where $T_1 = 1$ is a one-year period; $T_2 = 0.5$ is a half-year period; A_i and φ_i are the amplitude and 315 phase, respectively; and ε is the fitting residual.

316 2.2.4 Composition analysis

Composition analysis is the process of combining or synthesizing two different states or characteristics of meteorological variables. By calculating the sample means of both variables, it allows us to compare whether there are significant differences between the two states. The significance level is determined using t-tests:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}} \cdot \frac{1}{\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}},$$
(6)

where $\overline{x_1}$ and $\overline{x_2}$, s_1^2 and s_2^2 , and n_1 and n_2 are the means, variances, and sample sizes of the two states (1 and 2), respectively. This equation follows a t-distribution, and the degrees of freedom (df) are equal to $n_1 + n_2 - 2$. 324 3 Results

325 3.1 Long-term and seasonal variations in water levels in the Tianshan lake complex

326	We utilized lake water level data products derived from multisource altimetry satellite data
327	released by various institutions to obtain a time-series of the water level changes in the lake
328	complex within the study area (Figure 2a). The trends in the water level changes of the lakes in the
329	Tianshan region exhibited distinct characteristics, and the roles of glacier melting and
330	anthropogenic factors cannot be overlooked in these lake level variations. Taking Lake Bosten's
331	water level changes as an example, its water level variation differed significantly from those of the
332	other lakes. Lake Bosten's water level has been continuously decreasing since 2002, reaching a
333	minimum in 2014, followed by a gradual recovery after 2016. The overall water level change
334	trend was V-shaped. This is attributed to the accelerated glacier retreat in the region after 2016 (Yi
335	et al., 2016), which led to significant replenishment of Lake Bosten's water source. The lake's
336	water level reached its peak around 2020 and has been declining since then. This implies that, in
337	the long term, glacier melting could adversely impact the ecological environment around Lake
338	Bosten. Moreover, the inconsistent characteristics of the water level changes of the different lakes
339	primarily arise from the differences in their geographic distribution. Taking Lake Kapchagay and
340	Lake Balkhash as examples, the Ili River provides 70-80% of the runoff from Kapchagay Lake to
341	Lake Balkhash (de Boer et al., 2021). These lakes rely on precipitation and snowmelt for their
342	water supply. The water storage in Kapchagay Lake affects the water level of Lake Balkhash, and
343	changes in Kapchagay Lake's water level precede those of Lake Balkhash (red and blue solid lines
344	in Figure 2a).

345	All of the lakes within the lake complex exhibit significant annual, semi-annual, and medium-
346	to long-term periodic signals, which are manifested by the presence of approximately 6.9-year
347	periodic signals in the frequency spectra of most of the lakes (Figure 2b). Chen et al. (2017)
348	analyzed the strength and time-frequency characteristics of nearly 65 years of El Niño-Southern
349	Oscillation (ENSO) events from January 1951 to May 2016, using indices such as the Oceanic
350	Niño Index (ONI), the Southern Oscillation Index (SOI), and the multivariate ENSO index (MEI).
351	They reported 22 warm events (El Niño) and 13 cold events (La Niña) during this period.
352	Frequency analysis of ENSO characteristics revealed a higher occurrence of strong El Niño
353	months compared to strong La Niña months. The ENSO cycle primarily exhibited a periodicity of
354	2-7 years and also exhibited a decadal variability of 10-16 years. Thus, the 6.9-year periodic
355	signal observed in this study is consistent with the findings of Chen et al. (2017), suggesting that
356	the underlying physical mechanism behind the lake water storage variations in the Tianshan region
357	is fundamentally influenced by the ENSO. Additionally, Yi and Sun (2014) identified a 5-year
358	cycle in the Pamir and Kunlun regions, while Wen et al. (2023) used longer-span data to identify a
359	cycle of close to 6.6 years. The 6.9-year periodicity observed in our study of the lake complex
360	seems to encompass the range of 5-7 years and is likely influenced by the Arctic Oscillation and
361	El Niño–Southern Oscillation.

From 2002 to 2022, the long-term trend of the water level changes in the lake complex in the Tianshan region (weighted by the area of all of the lakes) was 0.01 m/a (0.73±0.10 Gt/a). Figure presents the spatiotemporal distribution of the annual variations in the water levels of the individual lakes in the Tianshan region from 2002 to 2022. The change periods of the different lakes are indicated based on the month of the peak water levels. Among the eight lakes studied, four lakes in the northeast exhibited rising water levels, with an average rate of increase of 0.06 \pm 0.001 m/a (ranging from 0.004 to 0.082 m/a). In contrast, four lakes in the southwest experienced declining water levels, with an average decrease rate of -0.006 ± 0.00003 m/a (ranging from -0.0182 to -0.01 m/a). The seasonal variation cycle of the eight lakes in the Tianshan region shows that the peak water levels occurred in May, June, and July, but Lake Bosten's peak water level occurred in March. This spatial heterogeneity in the timing of the lake level changes highlights the variability in the lake cycles.

374 Importantly, there were two significant instances of anomalous water level changes in the lake 375 complex. These occurred around 2010 and 2016. The primary sources of the water input to the 376 Tianshan lake complex were precipitation, ice melting, and anthropogenic factors, and 377 precipitation was the fundamental factor. By performing a singular spectrum decomposition on the 378 time series of the water level changes for each lake and selecting the first component for 379 differencing, the rate of change of the lake water levels was obtained (Figure 2d). The differenced 380 lake water level changes clearly highlight the impact of increased precipitation on the lake water 381 levels. Abnormal precipitation occurred in both the 2008–2010 and 2014–2016 periods, leading to 382 noticeable water level anomalies across all of the lakes, albeit with distinct time lags. Notably, 383 Lake Kapchagay (Lake 2, blue line) exhibited synchronized peaks and three periods of increased 384 precipitation in 2010, 2013, and 2016. In contrast, Lake Zaysan (Lake 6, green line) exhibited a 385 peak in 2013, instead of in 2016. This suggests that Lake Zaysan's water level changes were 386 affected by anthropogenic factors and reflect the implementation of flood prevention measures. 387 The spatiotemporal characteristics of these two instances of anomalous lake water level changes 388 will be further analyzed in the subsequent section.



Figure 2. (a) Time series of water level changes and corresponding precipitation variations for the lake complex within the study area from 2002 to 2022. The lake numbers are the same as in Figure 1. (b) Spectral transformations of water level changes for the eight lakes. (c) Peaks in lake level variations. Spatial distribution of peaks in lake level variations in the Tianshan region and the water level change trend for each lake. The lengths of the dashed arrows are not proportional to the other lakes' water level changes. (d) Differenced lake water level changes of the first component after singular spectrum analysis (SSA) decomposition. The curves of the same color represent the same lake, and the green shaded regions denote the two anomalous periods.

398	In addition to the long-term trends in the lake water levels, in this study, we further
399	investigated the seasonal trends of the lake levels. The seasonal trends capture the changes during
400	specific months of the year within the study period (e.g., the trend for spring covers March-May
401	each year). We divided the year into four seasons: spring (March-May), summer (June-August),
402	autumn (September-November), and winter (December-February). Figure 3 illustrates the
403	seasonal trends of the water levels of the individual lakes within the Tianshan region from 2002 to
404	2022. The seasonal interannual trends of the eight lakes in the Tianshan region exhibited similar
405	patterns, with a rate of 0.0128±0.001 m/a in spring, 0.0141±0.001 m/a in summer, and
406	0.0073±0.001 m/a in autumn and winter. Furthermore, lakes Alakol, Zaysan, and Ulungur all
407	exhibited increasing seasonal water level trends, while Lake Issyk-Kul and Lake Bosten exhibited
408	decreasing trends. Lake Balkhash exhibited an increasing trend in summer and a decreasing trend
409	during the other seasons, contributing to the overall long-term decreasing trend of the lake. Lake
410	Kapchagay exhibited an increasing trend in spring and a decreasing trend in the other seasons. The
411	water level changes of Lake Balkhash and Lake Kapchagay exhibited opposite trends in spring
412	and summer.



Figure 3. Spatiotemporal characteristics of the seasonal trends of the lake water levels of the lakes in the Tianshan region from 2002 to 2022: (a) Spring (MAM); (b) Summer (JJA); (c) Autumn (SON); and (d) Winter (DJF). The time series of the water-level changes for all of the lakes in each season are shown in the insets, the black line is the area-weighted lake level time series, and the numbers above the insets are the overall trends based on the area-weighted water level trends. Please note that the arrows of different colors indicate different magnitude levels.

420 3.2 Spatiotemporal variations in lake water storage during two anomalous periods



425	changes in the lake surface areas in the Tianshan lake complex during the two anomalous periods.
426	Similar to the changes in the water levels, the variations in the lake surface areas also exhibited
427	two transition periods. During the first anomalous period, except for Lake Balkhash's contraction
428	(decrease from 959.68 km ² to 931.87 km ² , i.e., by 28.81 km ²), the surface areas of the other lakes
429	increased. The total lake surface area for the entire region changed an $35,230.15$ km ² to $35,345.55$
430	km ² , i.e., an increase of 115.4 km ² . In the second anomalous period, the surface areas of all of the
431	lakes increased, and the total lake area increased from 35,425.56 km ² to 35,580.55 km ² , i.e., a total
432	increase of 154.99 km ² . To further analyze the spatial changes in the lakes, Figure 4a displays
433	subfigures that highlight the spatial patterns of the area changes for Kapchagay Lake, Zaysan
434	Lake, and Lake Balkhash. Kapchagay Lake exhibited significant area changes from 2008 to 2010,
435	while Zaysan Lake and Lake Balkhash exhibited evident changes during the second anomalous
436	period. Notably, the lakes with pronounced area changes were mainly located in the low-lying
437	areas where rivers flowed into the lakes. In addition to the clearly visible area changes during the
438	two anomalous periods, each lake experienced maximum and minimum area values during the
439	entire study period (Table 2). During the entire study period, from 2002 to 2021, Zaysan Lake
440	exhibited the largest area change, reaching 779.45 km², while Sasykkol Lake exhibited the
441	smallest change (7.57 km ²). The maximum area change for each lake is presented in Table 2.

Table 2. Comparison of maximum and minimum areas of the lakes in the Tianshan lake complex from 2002 to2021

No.	Lake name	Maximum area (km ²)	Minimum area (km²)	Area change (km ²)
1	Balkhash	17118.95	16821.48	297.47
2	Kapchagay	1256.46	1094.31	162.15
3	Issykku	6214.51	6205.74	8.77

4	Sasykkol	754.72	747.15	7.57
5	Alakol	3097.39	2956.20	141.19
6	Zaysan	4861.01	4081.56	779.45
7	Ulungur	869.71	840.85	28.86
8	Bosten	1095.09	887.62	207.47

445	Estimating the variations in the lake water storage is crucial for studying the mass balance in
446	the Tianshan region. By utilizing lake water level changes obtained from altimetry data and lake
447	area changes obtained from remote sensing imagery, we established water level-area relationships
448	for each lake and then estimated the water volume changes for all of the lakes (Figure 4a). The
449	calculation results reveal that from 2003 to 2022, most of the lakes experienced two anomalous
450	periods, during which significant water volume changes occurred. At the annual scale, the
451	cumulative water volume change results (orange solid line in Figure 4a) indicate that there were
452	distinct variations during the anomalous periods. To study the overall water volume changes in the
453	entire region, in this study, we summed the water volume changes for all of the lakes. Figure 4b
454	presents the mass variations of the total water storage in the Tianshan lake complex. Two distinct
455	periods of water volume increase can be identified. During the two-year period from 2010 to 2011,
456	the total mass of the lake water mass increased by 25.07 Gt, and during the two-year period from
457	2016 to 2017, the total water mass increased by 14.66 Gt. It should be noted that after 2018, the
458	total lake water mass in the study area decreased continuously, with a reduction of greater than 10
459	Gt/a after 2020.



461 Figure 4. (a) Time series of water storage changes (blue) and cumulative water storages (orange) for the various 462 lakes in the Tianshan region from 2002 to 2022. The lake area changes for Kapchagay Lake, Zaysan Lake, and 463 Bosten Lake during 2008–2010 and 2014–2016 are indicated by the red arrows. (b) Time series of total water 464 storage changes for all of the lakes in the study area. The red bars represent the annual water storage changes in the 465 lake complex, and the orange solid line represents the cumulative change in the water storage. The pink and green 466 shaded areas represent the dry and wet periods, respectively.

To study the impact of the anomalous lake water storage during the two anomalous periods on the regional mass balance, we obtained total mass change data for the Tianshan region from the GRACE satellite mission. Zhang et al. (2019) assessed the suitability of using GRACE mascon data for the Tianshan region and reported good agreement with GRACE spherical harmonic products across the entire area. Hence, in this study, we utilized GRACE mascon data provided by

473	three major institutions (CSR, JPL, and GSFC) to derive the total mass change rates for the study
474	area from 2002 to 2021, which were -7.41±0.35 Gt/a, -7.51±0.34 Gt/a, and -9.56±0.37 Gt/a, with
475	an average rate of change of -8.16 ± 0.36 Gt/a. It is important to note that during the study period,
476	these mass change results also contained two anomalous periods, which corresponded with the
477	anomalous periods of the water level changes in the lake complex discussed earlier. During the
478	two anomalous periods, the total mass increased by 65.73 Gt and 67.35 Gt, respectively. The
479	changes in the lake surface area during these periods constituted merely 0.01% and 0.014% of the
480	entire study area, but the contribution of the mass changes during the two anomalous periods
481	accounted for 22% and 14%, respectively. This indicates that the lake water storage variations had
482	a significant influence on the regional mass balance during the anomalous periods.

483 Changes in lake water storage are part of the regional mass variations and are closely 484 connected to changes in the soil moisture, snow water, and groundwater. The characteristics of the 485 changes in the other components will be analyzed specifically in the discussion section.

486 **3.3** Physical mechanism behind the two anomalous periods

In the previous section, we calculated and analyzed the long-term and seasonal variations in the lake water and the variations in the two anomalous period in the Tianshan region. The occurrence of two anomalous periods in the Tianshan region, reflected by the lake water levels and area changes, was significantly influenced by the abnormal variations in the precipitation. Therefore, understanding the physical causes behind the anomalies in the precipitation is crucial. Figures 5a and 5b display the strong correlation between the annual average precipitation in the Tianshan region and the ENSO (r=0.55, p<0.01). To further analyze the connection between the 494 lake water storage in the two anomalous periods and precipitation, in this section, we employ a 495 composite analysis method to delve into the physical mechanisms underlying the abnormal 496 precipitation. Similar methodologies have also been applied to study the responses of lakes on the 497 Qinghai–Tibet Plateau to climate (Lei et al., 2019). Figure 5c indicates that during El Niño-498 dominated years (1994, 1997, 2002, 2004, 2006, 2010, and 2016), the precipitation in the 499 Tianshan region tended to increase.





501

502 Figure 5. (a) Annual average precipitation in the Tianshan region; (b) ENSO index; (c) Precipitation anomalies



the student's t-test.

506

507 As one of the world's largest mid-latitude arid regions, the Tianshan area is susceptible to the

508	impacts of global climate change (Zhang et al., 2022b). The occurrence of precipitation requires
509	the convergence of significant amounts of water vapor, and the distribution of the water vapor
510	affects the formation of clouds and precipitation, aerosol growth, and other phenomena, thereby
511	playing a crucial role in meteorological phenomena and climate conditions (Grossi et al., 2015).
512	We observed that the spatial distribution of the precipitation anomalies in 2010 and 2016 (Figures
513	6c, d) closely resembled the spatial distribution of the total atmospheric water vapor content
514	(Figures 6a, b). This correspondence indicates that the water vapor content in the study area
515	increased during these years, creating favorable conditions for precipitation. Notably, the water
516	levels of the lakes in the Tianshan region peaked in 2006, which was an El Niño year. To validate
517	the increase in precipitation during these years, we compared the precipitation amounts in 2006,
518	2010, and 2016 with the climatic average. Figure 6e shows that the precipitation in 2006 did not
519	pass the significance testing, suggesting that the water level increase in 2006 may have been
520	caused by other factors, such as snowmelt. In contrast, the years with two instances of anomalous
521	mass changes (2010 and 2016) exhibited more pronounced increases in precipitation compared to
522	the El Niño-dominated years (1994, 1997, 2002, 2004, 2006, 2010, and 2016) (Figure 5c), with
523	significance demonstrated at the 90% confidence level (Figures 6c, d). Furthermore, during the
524	anomalous periods in 2010 and 2016, the vertical wind field intensity at 500 hPa also exhibited
525	enhancement along the Tianshan mountain range (Figure 6f). This intensified vertical motion
526	facilitated the convergence of more water vapor in the study area, leading to increased
527	precipitation. Consequently, the Tianshan region experienced two significant mass anomalies in
528	2010 and 2016 due to these pronounced shifts in precipitation.



Figure 6. Distribution of atmospheric total water vapor anomalies during the two anomalous mass change periods
in the study area: (a) 2010 and (b) 2016. Anomalies in average precipitation in (c) 2010 and (d) 2016. (e)
Anomalies in average precipitation in 2006; (f) Anomalies in the 500-hPa vertical wind field during the two El
Niño years: 2010 and 2016. The dotted areas indicate significant values at the 90% confidence level determined
using the student's t-test.

535 4 Discussion

In this study, multisource remote sensing observations were utilized to investigate the water storage changes in the lake complex in the Tianshan region in China. Building upon the computation and analysis of the spatiotemporal distribution characteristics of the water storage changes in the lake complex, we identified two major anomalous periods (2010 and 2016). 540 Considering the presence of various other hydrological components in the Tianshan region, further 541 discussion is warranted regarding the spatiotemporal distribution characteristics of the quality 542 changes in the different hydrological components, their variations during the two anomalous 543 periods, and the resulting load deformation effects on the surface GNSS observations.

4.1 Characteristics of changes in various hydrological components and their relationship with lake water storage variations

546 The total mass changes in the Tianshan region were highly complex, and the variations in the 547 lake water storage represent only one facet of the hydrological changes in the surrounding area. 548 These variations were closely related to other hydrological components such as glaciers, soil 549 moisture, groundwater, and the snowmelt equivalent. However, it remains unclear to what extent 550 each hydrological component contributed to the changes in the lake water storage, that is, what 551 proportion of the total mass changes each component accounted for in the study area. This 552 warrants further exploration and analysis. To address this, we initially employed GRACE satellite 553 gravity data to deduce the overall mass changes across the study area. Then, by utilizing a range of 554 remote sensing observations and hydrological models to separate individual hydrological 555 components, we analyzed the contribution of each component to the variations in the lake water 556 storage within the context of the regional mass changes. The variations in each hydrological 557 component encompassed long-term trends and periodic fluctuations. Once these variations were 558 effectively isolated, further research and analysis could be conducted to delve into the 559 characteristics of the changes in each hydrological component during the two anomalous periods 560 of lake water fluctuations.

561

Using the data provided by Barandun et al. (2020) and Hugonnet et al. (2021), we calculated

562	the glacier melting rates in each sub-region of the Tianshan region (Figure 7). The results indicate
563	that significant glacier mass loss occurred. Furthermore, the results show that the glacier melting
564	time series of Barandun et al. (2020) and Hugonnet et al. (2021) for the western Tianshan and
565	eastern Tianshan regions were consistent, while in the central Tianshan, Barandun et al. (2020)
566	estimated a slightly faster glacier melting rate. Barandun et al. (2020) estimated the annual glacier
567	melting rate in the Tianshan region to be -3.78 Gt/a from 2000 to 2018. Hugonnet et al. (2021)
568	estimated the glacier mass change time series for the Tianshan region and obtained a glacier
569	melting rate of -3.53 Gt/a from 2000 to 2021, which is close to the trend derived by Yi et al.
570	(2016) using ICESat data (-3.4 Gt/a). The two estimated glacier melting rates are quite consistent.
571	However, considering the periodic variations in the glaciers, in this study, we selected the glacier
572	change results of Hugonnet et al. (2021) for use in the subsequent research analysis.





575 Figure 7. Cumulative glacier change time series for the western, central, and eastern sub-regions of the Tianshan

region calculated using the data provided by Barandun et al. (2020) and Hugonnet et al. (2021). The background



579	In addition, we considered the changes in the soil moisture, canopy, snow water equivalent,
580	and groundwater. We used the GLDAS Noah hydrological model to calculate the soil moisture
581	changes in the Tianshan region. The results indicate a long-term increasing trend with a rate of
582	0.46±0.25 Gt/a. The changes in the canopy and its long-term trend were both close to zero, so the
583	effect of the canopy was neglected in this study. Furthermore, we extracted the trend of the snow
584	water equivalent (-0.06±0.11 Gt/a) from the ECMWF model, and the groundwater change rate
585	$(-0.08\pm0.04$ Gt/a) from the WGHM model. The time series of the mass changes for these
586	hydrological components after being subjected to a 1-year moving average are presented in Figure
587	8a. The results show that all of the hydrological components exhibited two periods of exceptional
588	fluctuations. These periods were consistent with the anomalous periods of lake water level
589	variations. The long-term trends of the snow water, groundwater, and glaciers were continuous
590	decreasing trends, while the soil moisture and lake water exhibited increasing trends. Based on
591	these findings, we infer that the ongoing melting of the glaciers in the Tianshan region contributed
592	to the increases in the lake water and soil moisture.

Regarding the long-term trends of the various hydrological components, the glacier melting 593 594 exhibited a significant rate of change, while the trends of the other hydrological components were 595 almost stable. Table 3 presents the long-term trends, annual amplitudes, and phases of the changes 596 in the hydrological components. The results show that the contribution of the lake water storage 597 changes to the total GRACE signal was negligible. Among the components, the glaciers exhibited 598 the largest rate of decrease, while the mass changes of the other hydrological components were 599 relatively stable. In particular, the two periods of exceptional fluctuations better reflect the impact 600 of each hydrological component on the overall mass balance in the Tianshan region. Although the

trend of the lake water changes was small, its contributions during the two anomalous periods were 22% and 14%, respectively, indicating significant increases in its contribution. The soil moisture and snow water signals predominantly contributed during the first period of change, accounting for 93.98% and 14.67%, respectively. During the second anomalous period, the contributions of the soil moisture and snow water were 69.25% and 20.83% (Figures 8b, c). During the two periods of mass anomalies, the soil moisture contributed significantly, while the changes in the snow and lake water made comparable contributions.

Figure 8d presents the interannual mass changes of each hydrological component. The snow water accumulated during the winter and spring and reached its peak in March. As temperature increased in summer, the snow gradually melted, and the soil moisture reached its peak in May, while the groundwater and lake water reached their peaks in July. In addition, the annual amplitudes of the snow water and soil moisture contributed significantly to the annual amplitude of the GRACE signal. This suggests that the total annual mass changes observed in the study area by GRACE were mainly driven by the snowmelt and the annual fluctuations in the soil moisture.



617 Figure 8. Mass change time series of the various hydrological components from 2002 to 2021: (a) Smoothed mass

618 change time series of each component. The dashed lines represent the mass differences during the two mass 619 anomaly periods from 2008 to 2010 and from 2014 to 2016. (b) The total mass and the increase in mass of each 620 hydrological component during the two mass anomaly periods. (c) The percentage contribution of each 621 hydrological component to the total mass increase during the two mass anomaly periods. (d) The intra-annual mass 622 variations of each hydrological component in the study area.

623

624

Table 3 Mass change rate of each hydrological component within the study area

Mass	Annual	Phase (days)	Trend (Gt/a)	Mass change	Mass change
component	amplitude (Gt)			during the first	during the
				anomaly (Gt)	second
					anomaly (Gt)
GRACE	32.87	98.60	-8.16±0.36	65.73	67.35
Soil moisture	10.56	94.53	0.46±0.25	61.77	46.64
lake	5.24	168.69	0.73±0.10	14.54	9.36
snow	31.71	36.95	-0.06±0.11	9.64	14.03
glacier	-	-	-3.53	-	-
groundwater	5.61	197.4	-0.08 ± 0.04	6.82	-
-: No data					

625

The spatial distributions of the precipitation, total mass changes monitored by GRACE, soil moisture, and snow water equivalent during the two anomalous mass change periods are presented in Figure 9. The spatial distribution of each hydrological component during these periods reflects the geographic variation in the precipitation. During the first anomalous mass change period, the largest total mass changes occurred in the western Tianshan region and the northern part of the study area, forming a strip-like pattern along the Tianshan Mountains. In contrast, during the second transition period, the mass increases were mainly concentrated in the lake region. The

633	spatial distribution of the mass increased during both anomalous periods (Figures 9c, d) and
634	closely corresponded to the spatial distribution of the increase in precipitation (Figures 9a, b),
635	suggesting that the increased precipitation led to a corresponding increase in the soil moisture,
636	resulting in an overall mass increase across the study area. By comparing the spatial distributions
637	of the soil moisture (Figures 9e, f) and the snow water equivalent (Figures 9g, h), we found that
638	the areas with increased soil moisture were primarily located within the lake region. By comparing
639	the changes in the snow water and lake water shown in Figure 8a, we inferred that the interannual
640	lake water level changes were not solely driven by direct rainfall. With increasing temperature, the
641	accumulated snow began to melt and slowly infiltrated into the soil, leading to an increase in the
642	soil moisture. The increase in the soil moisture was subject to a certain time delay in response to
643	the changes in the snow water. Liu et al. (2022) reported that a substantial amount of rainfall
644	needs time to saturate the soil after falling and subsequently enters the lakes via surface runoff.
645	Hence, the peak water levels of the lakes occurred during the troughs of the snow water
646	distribution.



648 Figure 9. Spatial distribution of the changes in precipitation (a, b), the total hydrological mass changes observed

by GRACE (c, d), the soil moisture (e, f), and the snow water equivalent (g, h) during the two anomalous mass
change periods within the study area. The left column (a, c, e, g) corresponds to the first anomalous mass change
period in 2010, while the right column (b, d, f, h) corresponds to the second anomalous mass change period in
2016.

647

654 4.2 Load correction and its impact on GNSS observations

The aforementioned changes in the lake complex and the various hydrological components, as well as the two instances of precipitation anomalies, were invariably associated with the significant mass anomalies, which were evident in the time-variable gravity signals inferred from

658	GRACE. These mass change signals undeniably induced surface loading effects on the solid
659	Earth's surface, which should also be reflected in the surface displacement field. To verify whether
660	this signal was captured in the vertical displacements monitored via a GNSS, we employed GNSS
661	data provided by the Nevada Geodetic Laboratory
662	(http://geodesy.unr.edu/NGLStationPages/stations/) to calculate the surface displacements. Due to
663	the temporal coverage of the GNSS data, we selected GNSS stations with time series that
664	encompassed the mass anomaly periods. To derive the vertical displacements induced by the
665	surface mass changes, we removed the contributions of the global atmospheric loading and non-
666	tidal ocean loading effects from the vertical displacements at these GNSS stations. The resulting
667	residual signals were then used to analyze the surface mass changes. We employed the empirical
668	mode decomposition (EMD) method to filter and smooth the GNSS signals (He et al., 2020). After
669	corrections for atmospheric and non-tidal ocean loading effects, the selected GNSS stations
670	provided time series that clearly exhibited changes in the vertical surface displacements due to the
671	mass anomalies during the two wet-to-dry transition periods (left column in Figure 10). The
672	results show that during the first mass anomaly period in 2010, GNSS station SELE exhibited a
673	significant jump in the vertical displacement, while stations CHUM and TALA exhibited
674	downward trends during both mass anomaly periods. This suggests that the magnitudes of the
675	mass changes generated by the two mass anomalies were sufficient to induce noticeable surface
676	deformations that could be detected by the GNSS.



679 Figure 10. Time series of vertical displacements at GNSS stations in the Tianshan region (left column) and the
680 changes in the sliding trends at the corresponding stations (right column). The sliding long-term trends have been
681 corrected for the vertical displacement due to the loading effects obtained by integrating GRACE mascon data with
682 Green's functions.

684 When analyzing the impact of the surface mass changes on the GNSS displacement field, 685 scientists often calculate the loading effect of the surface mass migration rate on the GNSS 686 displacement field (Rao and Sun, 2022; Wen et al., 2023). However, constructing a surface mass 687 change model is an extremely challenging task as it requires considering solid crustal 688 displacement, the mass migration associated with surface erosion/deposition, and more accurate 689 hydrological models (especially for groundwater). Since we focused solely on the surface mass 690 migration, particularly the two anomalous mass changes and their impacts on the GNSS 691 displacement field, in this study, we selected the GRACE mascon data as the global mass change

692	model and used the Green's function integration method to calculate the vertical displacement
693	caused by these loads at the three GNSS stations in order to explore the effect of correcting the
694	surface mass changes on the GNSS vertical displacements. By considering the time span of the
695	GNSS time series at each station, we then selected 100 months, 120 months, and 120 months of
696	GNSS time series for the SELE, CHUM, and TALA stations, respectively. We applied a moving
697	window with a monthly step to calculate and correct the loading vertical displacements. As a
698	result, we obtained the long-term trend of the displacement variations at the GNSS stations with
699	the sliding window changes (right column in Figure 10). The results presented in Figure 10 show
700	that after the loading correction, the stability of the vertical displacement trend variations at the
701	three stations (CHUM, SELE, and TALA) were all improved. Specifically, the standard deviation
702	of the sliding trend at CHUM, SELE, and TALA stations decreased by 33%, 27%, and 35%,
703	respectively. This indicates that the surface mass changes had a non-negligible impact on the
704	GNSS displacement field. After correcting for the mass change loading, the true crustal
705	displacement field was restored and was represented more accurately. Therefore, when studying
706	regional tectonic movements, it is essential to perform surface mass loading corrections.

708 4.3 Error Analysis of Mass Balance in the Tianshan Region

It is important to note that in Section 4.1, the calculated GRACE total mass change did not perfectly match the sum of the contributions of the various hydrological components, indicating that there were some uncertainties in the mass changes calculations for each hydrological component. To investigate the sources of these uncertainties, we truncated the GRACE mascon data and the multisource land surface mass change rate model to 60° and applied Gaussian 300 km

714	filtering and P4M6 decorrelation filtering. By comparing Figures 11a and 11b, it can be seen that
715	both the GRACE data and the land surface model agree well in the central and western Tianshan
716	regions, but there are significant discrepancies in the eastern Tianshan region (Figure 11c). The
717	reasons for these discrepancies are rather complex. Upon careful analysis, we found that the
718	regions with residual signals in Figure 11c contain densely distributed cities and also include oil
719	and gas extraction areas (such as the Karamay oilfield). Therefore, the groundwater in these
720	regions may experience significant depletion, and the current hydrological models are believed to
721	severely underestimate the changes in the groundwater (Döll et al., 2012; Scanlon et al., 2019),
722	which could be one of the uncertainties. Furthermore, the problem of solid mass migration in the
723	Tianshan region is highly complex (Rao and Sun, 2022; Wen et al., 2023), and research on factors
724	such as erosion, sedimentation, and crustal movement needs to be further improved and refined. In
725	conclusion, the various hydrological models used in this study contain significant uncertainties.
726	Future research on regional mass balance will rely on continually refining hydrological and
727	surface solid mass models.



Figure 11. (a) Mass change rate in the Tianshan region obtained by truncating and filtering the GRACE mascon
data; (b) Land surface mass change rate model truncated to 60° and processed using the same filters as GRACE;
and (c) Difference between the truncated and filtered GRACE mascon data and the land surface mass change rate
model.

735 5 Conclusions

In this study, we utilized multiple remote sensing datasets and hydrological models to investigate the spatiotemporal distribution characteristics of the lake water storage changes in the Tianshan region from 2002 to 2022. Two significant periods of water storage anomalies were identified during the study period. Additionally, we analyzed and calculated the contributions and proportions of the various hydrological components in the study area, and we discussed the influencing factors and physical mechanisms behind these hydrological changes. The main conclusions of this study are as follows.

743 The results of this study revealed that the lake water storage in the Tianshan region exhibited

744	a long-term increasing trend with a rate of 0.73±0.10 Gt/a. We also identified two periods of water
745	storage anomalies during 2008-2010 and 2014-2016. The results indicate that all of the lakes
746	exhibited significant annual and semi-annual periodic variations, as well as medium- to long-term
747	signals of approximately around 6.9 years, while Zaysan Lake exhibited a 4.1-year periodicity,
748	which was possibly due to the influence of anthropogenic factors. The 6.9-year periodic signal
749	was associated with the melting of ice and snow, which was influenced by the Arctic Oscillation
750	and El Niño-Southern Oscillation. The seasonal interannual trends of the lake complex in the
751	Tianshan region exhibited similar patterns, with rates of 0.0128±0.001 m/a in spring,
752	0.0141±0.001 m/a in summer, and 0.0073±0.001 m/a in autumn and winter. In addition, during the
753	two-year periods of 2010–2011 and 2016–2017, the total lake water storage in the Tianshan region
754	increased by 25.07 Gt and 14.66 Gt, respectively. However, after 2017, the total lake water storage
755	in the study area began to decrease continuously, with annual reductions of over 10 Gt in 2020 and
756	2021. This trend requires further observation and investigation.
757	In addition, the contributions and proportions of the various hydrological components in the
750	CDACE simplements also had and assessed at The manife manufacture and the state as it maintains

758 GRACE signal were calculated and separated. The results revealed that the soil moisture, snow 759 water equivalent, lake water, and vertical displacements observed by the GNSS all reflected the 760 two mass change anomalies. During the two anomalous periods, the changes in the lake area 761 accounted for only 0.01% and 0.014% of the total area, but the contributions of the lake water 762 increased significantly, by 22% and 14%, respectively. The contributions of the soil moisture and 763 snow water during the first anomalous period were 93.98% and 14.67%, respectively, while their 764 contributions during the second anomalous period were 69.25% and 20.83%, respectively. During 765 the two anomalous periods, the soil moisture was the primary contributor, and the snow changes

and lake water storage made roughly equal contributions. The annual water level changes in the
lake complex were not only directly affected by rainfall but also significantly influenced by ice
and snow meltwater.

We also identified a close correlation between the two mass change anomaly periods and the ENSO events (r=0.55, p<0.01). During El Niño-dominated years, the atmospheric water vapor content in the Tianshan region generally increased, leading to corresponding increases in precipitation. In the two anomaly years (2010 and 2016), the increase in precipitation was even more pronounced, and the vertical wind field was strengthened. These conditions led to more water vapor descending and converging in the study area, providing favorable conditions for precipitation and resulting in the occurrence of the two mass change anomalies.

By considering the lake water storage changes in conjunction with the other hydrological components, this study provides a new perspective for investigation of the mass balance in the Tianshan region. The research results highlight the need to focus on the impact of extreme climate events on the regional mass balance in the context of global climate change.

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781 CRediT authorship contribution statement

782 Zhiqiang Wen: Conceptualization, Data curation, Formal analysis, Writing – original draft.

- 783 Wenke Sun: Conceptualization, Funding acquisition, Writing review & editing. Shuang Yi:
- 784 Conceptualization, Funding acquisition, Investigation, Writing review & editing.

785

786 Declaration of competing interest

787 The authors declare that they have no known competing financial interests or personal

relationships that could have appeared to influence the work reported in this paper.

789

790	Data Availability Statement
791	GNSS data: http://geodesy.unr.edu/NGLStationPages/stations/; Lake level data:
792	https://nsidc.org/data/icesat-2/products, https://eocat.esa.int/sec/#data-services-area,
793	http://hydrolare.net/catalogue.php. GPCC Precipitation:
794	https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html Wind field data:
795	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview
796	Atmospheric water vapor data: <u>https://doi.org/10.5281/zenodo.5776718</u> . Groundwater
797	datasets: https://doi.pangaea.de/10.1594/PANGAEA.918447
798	
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803	(https://ldas.gsfc.nasa.gov/gldas/), GRACE/GRACE-FO Mascon data are available at
804	http://grace.jpl.nasa.gov, http://www2.csr.utexas.edu/grace and
805	https://earth.gsfc.nasa.gov/geo/data/grace-mascons
806	
807	References
808	Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., Livingstone, D. M.,

809 Sommaruga, R., Straile, D., VanDonk, E., Weyhenmeyer, G. A., and Winder, M. (2009). Lakes

810	assentinels of climate change. Limnology and Oceanography, 54(6), 2283-2297.
811	Bai, P., Liu, X., Yang, T., Liang, K., and Liu, C. (2016). Evaluation of streamflow simulation results of
812	land surface models in GLDAS on the Tibetan plateau. Journal of Geophysical Research:
813	Atmospheres, 121(20), 12-180.
814	Barandun, M., Pohl, E., Naegeli, K., McNabb, R., Huss, M., Berthier, E., et al. (2021). Hot spots of
815	glacier mass balance variability in Central Asia. Geophysical Research Letters, 48,
816	e2020GL092084.
817	Borger, C., Beirle, S., and Wagner, T. (2021). A 16-year global climate data record of total column
818	water vapour generated from OMI observations in the visible blue spectral range. Earth
819	System Science Data Discussions, 1-25.
820	Brun, F., Berthier, E., Wagnon, P., Kääb, A., and Treichler, D. (2017). A spatially resolved estimate of
821	high mountain Asia glacier mass balances from 2000 to 2016. Nature Geoscience, 10(9), 668-
822	673.
823	Chen, H., Xu, F., Li, X., Xia, T., Zhang Y. (2017). Intensities and time-frequency variability of enso in
824	the last 65 years. Journal of Tropical Meteorology, 33(5): 683-694.
825	Cheng, M., Ries, J. C., and Tapley, B. D. (2011). Variations of the Earth's figure axis from satellite laser
826	ranging and GRACE. Journal of Geophysical Research, 116, B01409.
827	Deng, H., and Chen, Y. (2017). Influences of recent climate change and human activities on water
828	storage variations in Central Asia. Journal of Hydrology, 544, 46-57.
829	de Boer, T., Paltan, H., Sternberg, T., and Wheeler, K. (2021). Evaluating vulnerability of Central Asian
830	water resources under uncertain climate and development conditions: The case of the Ili-
831	Balkhash Basin. Water, 13(5), 615

- 832 Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., ... and Scanlon, B.
- R. (2012). Impact of water withdrawals from groundwater and surface water on continental
 water storage variations. Journal of Geodynamics, 59, 143-156.
- 835 Farinotti, D., Longuevergne, L., Moholdt, G., Duethmann, D., Mölg, T., Bolch, T., et al. (2015).
- 836 Substantial glacier mass loss in the Tien Shan over the past 50 years. Nature Geoscience, 8(9),
 837 716–722.
- 838 Gardelle, J., Berthier, E., and Arnaud, Y. (2012). Slight mass gain of Karakoram glaciers in the early
 839 twenty-first century. Nature Geoscience, 5(5), 322-325.
- 840 Gardelle, J., Berthier, E., Arnaud, Y., and Kääb, A. (2013). Region-wide glacier mass balances over the
- Pamir-Karakoram-Himalaya during 1999–2011. The Cryosphere, 7(4), 1263-1286.
- 842 Grant, L., Vanderkelen, I., Gudmundsson, L., Tan, Z., Perroud, M., Stepanenko, V. M., ... and Thiery,
- W. (2021). Attribution of global lake systems change to anthropogenic forcing. Nature
 Geoscience, 14(11), 849-854.
- 845 Grossi, M., Valks, P., Loyola, D., Aberle, B., Slijkhuis, S., Wagner, T., Beirle, S., and Lang, R. (2015).
- 846 Total column water vapour measurements from GOME-2 MetOp-A and MetOp-B,
- 847 Atmospheric Measurement Techniques, 8, 1111–1133.
- 848 He, X., Yu, K., Montillet, J. P., Xiong, C., Lu, T., Zhou, S., ... and Ming, F. (2020). GNSS-TS-NRS: An
- 849 Open-source MATLAB-Based GNSS time series noise reduction software. Remote Sensing,
 850 12(21), 3532.
- 851 Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey,
- 852 C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023):
- 853 ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change

- 854 Service (C3S) Climate Data Store (CDS)(Accessed on 30-Apr-2023).
- Heki, K. (2004). Dense GPS Array as a New Sensor of Seasonal Changes of Surface Loads.
- 856 Geophysical Monograph Series.
- 857 Heki, K., and Arief, S. (2022). Crustal response to heavy rains in Southwest Japan 2017-2020. Earth
- and Planetary Science Letters, 578, 117325.
- 859 Hu, Z., Zhou, Q., Chen, X., Li, J., Li, Q., Chen, D., et al. (2018). Evaluation of Three Global Gridded
- 860 Precipitation Data Sets in central Asia Based on Rain Gauge Observations. International
 861 Journal of Climatology, 38 (9), 3475–3493.
- Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M.,
- Bossaillant, I., Brun, F. and Kääb, A. (2021). Accelerated global glacier mass loss in the early
 twenty-first century Dataset. [Dataset]. Theia.
- 865 Jacob, T., Wahr, J., Pfeffer, W. T., and Swenson, S. (2012). Recent contributions of glaciers and ice caps
- to sea level rise. Nature, 482(7386), 514-518.
- 867 Jean-Francois P., Andrew C., Noel G., Alan S. B. (2016). High-resolution mapping of global surface
- 868 water and its long-term changes. Nature, 540, 418-422.
- 369 Jiang, L., Nielsen, K., Andersen, O. B., and Bauer-Gottwein, P. (2017). Monitoring recent lake level
- 870 variations on the Tibetan Plateau using CryoSat-2 SARIn mode data. Journal of Hydrology,
- **871** 544, 109-124.
- 872 Kääb, A., Berthier, E., Nuth, C., Gardelle, J., and Arnaud, Y. (2012). Contrasting patterns of early
- 873 twenty-first-century glacier mass change in the Himalayas. Nature, 488(7412), 495-498.
- 874 Kääb, A., Treichler, D., Nuth, C., and Berthier, E. (2015). Contending estimates of 2003–2008 glacier
- 875 mass balance over the Pamir–Karakoram–Himalaya. Cryosphere, 9(2), 557-564.

876	Lei, Y., Zhu, Y., Wang, B., Yao, T., Yang, K., Zhang, X., and Ma, N. (2019). Extreme lake level
877	changes on the Tibetan Plateau associated with the 2015/2016 El Niño. Geophysical Research
878	Letters, 46(11), 5889-5898.
879	Li, W., Chen, Y., Yuan, X., Xiao, W., and Windley, B. F. (2022). Intracontinental deformation of the
880	Tianshan Orogen in response to India-Asia collision. Nature Communications, 13(1), 3738.
881	Li, Y. A., Tan, Y., Jiang, F. Q., Wang, Y. J., and Hu, R. J. (2003). Study on hydrological features of the
882	Kaidu River and the Bosten Lake in the second half of 20th century. Journal of Glaciology and
883	Geocryology, 25(2), 215-218.
884	Liu, C., Hu, R., Wang, Y., Lin, H., Zeng, H., Wu, D., and Shao, C. (2022). Monitoring water level
885	and volume changes of lakes and reservoirs in the Yellow River Basin using ICESat-2 laser
886	altimetry and Google Earth Engine. Journal of Hydro-environment Research, 44, 53-64.
887	Liu, H., Chen, Y., Ye, Z. et al. (2019). Recent Lake Area Changes in Central Asia. Scientific Reports,

- **888** 9(1): 16277.
- 889 Loomis, B. D., Rachlin, K. E., Wiese, D. N., Landerer, F. W., and Luthcke, S. B. (2020). Replacing
- 890 GRACE/GRACE-FO with satellite laser ranging: Impacts on Antarctic Ice Sheet mass change.
- 891 Geophysical Research Letters, 47(3), e2019GL085488.
- Matsuo, K., and Heki, K. (2010). Time-variable ice loss in Asian high mountains from satellite
 gravimetry. Earth and Planetary Science Letters, 290(1-2), 30-36.
- 894 Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., ... and Döll, P.
- 895 (2021). The global water resources and use model WaterGAP v2. 2d: Model description and
 896 evaluation. Geoscientific Model Development, 14(2), 1037-1079.
- 897 Olthof, I., Fraser, R. H., and Schmitt, C. (2015). Landsat-based mapping of thermokarst lake dynamics

- 898 on the Tuktoyaktuk Coastal Plain, Northwest Territories, Canada since 1985. Remote Sensing899 of Environment, 168, 194-204.
- 900 Pan, Y., Chen, R., Yi, S., Wang, W., Ding, H., Shen, W., and Chen, L. (2019). Contemporary mountain-
- 901 building of the Tianshan and its relevance to geodynamics constrained by integrating GPS and
- 902 GRACE measurements. Journal of Geophysical Research: Solid Earth, 124(11), 12171-12188.
- 903 Pan, Y., Hammond, W. C., Ding, H., Mallick, R., Jiang, W., Xu, X., Shen, W. (2021). GPS Imaging of
- 904 Vertical Bedrock Displacements: Quantification of Two-Dimensional Vertical Crustal
 905 Deformation in China. Journal of Geophysical Research: Solid Earth, 126(4).
- 906 Pan, Y., Jiang, W., Ding, H., Shum, C. K., Jiao, J., and Li, J. (2023). Intradecadal fluctuations and three-

dimensional crustal kinematic deformation of the Tianshan and Pamir derived from multi-

- **908** geodetic imaging. Journal of Geophysical Research: Solid Earth, 128, e2022JB025325.
- 909 Peltier, W. R., D. F. Argus, and R. Drummond. (2018). Comment on the paper by Purcell et al. 2016
- 910 entitled An assessment of ICE-6G_C (VM5a) glacial isostatic adjustment model, Journal of
- 911 Geophysical Research: Solid Earth, 122.
- 912 Rinzin, S., Zhang, G., Sattar, A., Wangchuk, S., Allen, S. K., Dunning, S., and Peng, M. (2023). GLOF
- 913 hazard, exposure, vulnerability, and risk assessment of potentially dangerous glacial lakes in914 the Bhutan Himalaya. Journal of Hydrology, 619, 129311.
- 815 Rao, W., and Sun, W. (2022). Uplift of the Tibetan Plateau: How to accurately compute the
 816 hydrological load effect? Journal of Geophysical Research: Solid Earth, 127, e2021JB022475.
- 917 Schneider, U., Becker, A., Finger, P., Rustemeier E., Ziese, M. (2022). GPCC Monitoring Product:
- 918 Near Real-Time Monthly Land-Surface Precipitation from Rain-Gauges based on SYNOP and
- 919 CLIMAT data.

- 920 Scanlon, B. R., Zhang, Z., Rateb, A., Sun, A., Wiese, D., Save, H., ... and Reedy, R. C. (2019). Tracking
- 921 seasonal fluctuations in land water storage using global models and GRACE satellites.
 922 Geophysical Research Letters, 46(10), 5254-5264.
- 923 Swenson, S., Chambers, D., and Wahr, J. (2008). Estimating geocenter variations from a combination

924 of GRACE and ocean model output. Journal of Geophysical Research, 113, B08410.

- 925 Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., ... and Velicogna, I.
- 926 (2019). Contributions of GRACE to understanding climate change. Nature Climate Change,
- 927 9(5), 358-369.
- Tangdamrongsub, N., Han, S. C., Jasinski, M. F., and Šprlák, M. (2019). Quantifying water storage
 change and land subsidence induced by reservoir impoundment using GRACE, Landsat, and
 GPS data. Remote Sensing of Environment, 233, 111385.
- 931 Taube, C. M. (2000). Three methods for computing the volume of a lake. Manual of Fisheries Survey

932 Methods II: With Periodic Updates; Schneider, JC, Ed, 175-179.

- 933 Wang, X., Ding, Y., Liu, S., Jiang, L., Wu, K., Jiang, Z., and Guo, W. (2013). Changes of glacial lakes
- 934 and implications in Tianshan, central Asia, based on remote sensing data from 1990 to 2010.
- 935 Environmental Research Letters, 8(4), 044052.

936 Wang, H., Huang, Z., Wen, Z., and Luo, Z. (2022a). Lake Water Storage Changes in Northeast Hoh Xil

- 937 Observed by Cryosat-2 and Landsat-5/7/8: Impact of the Outburst of Zhuonai Lake in 2011.
- 938 IEEE Geoscience and Remote Sensing Letters, 19, 1-5.
- 939 Wang, Q., Yi, S., and Sun, W. (2017a). Precipitation-driven glacier changes in the Pamir and Hindu
- 940 Kush mountains. Geophysical Research Letters, 44(6), 2817-2824.
- 941 Wang, Q., Yi, S., Chang, L., and Sun, W. (2017b). Large-scale seasonal changes in glacier thickness

- 942 across High Mountain Asia. Geophysical Research Letters, 44(20), 10-427.
- 943 Wang, Q., and Sun, W. (2022b). Seasonal cycles of High Mountain Asia glacier surface elevation
- 944 detected by ICESat-2. Journal of Geophysical Research: Atmospheres, 127, e2022JD037501.
- 945 Wahr, J., Molenaar, M., and Bryan, F. (1998). Time variability of the Earth's gravity field: Hydrological
- and oceanic effects and their possible detection using GRACE. Journal of Geophysical
- 947 Research, 103(B12), 30205–30229.
- Wen, Z, Rao W, Sun W. (2023). Contribution of loading deformation to the GNSS vertical velocity
 field in the Chinese mainland, Geophysical Journal International, 233(3),1655–1670.
- 950 White, A. M., Gardner, W. P., Borsa, A. A., Argus, D. F., and Martens, H. R. (2022). A review of
- 951 GNSS/GPS in hydrogeodesy: Hydrologic loading applications and their implications for water
 952 resource research. Water Resources Research, 58(7), e2022WR032078.
- 953 Woolway, R. I. and Merchant, C. J. Worldwide alteration of lake mixing regimes in response to climate
- 954 change. Nature Geoscience, 12, 271–276 (2019).
- 955 Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M., and Sharma, S.
- 956 (2020). Global lake responses to climate change. Nature Reviews Earth & Environment, 1(8),
 957 388-403.
- Wu, D., Yan, H., and Yuan, S. (2018). L1 regularization for detecting offsets and trend change points in
 GNSS time series. GPS Solutions, 22(3), 1–5.
- 960 Wu, Y., Zheng, Z., Nie, J., Chang, L., Su, G., Yin, H., ... and Bo, W. (2022). High-Precision Vertical
- 961 Movement and Three-Dimensional Deformation Pattern of the Tibetan Plateau. Journal of
 962 Geophysical Research: Solid Earth, 127(4), e2021JB023202.
- 963 Xu, Y., Li, J., Wang, J., Chen, J., Liu, Y., Ni, S., ... and Ke, C. (2020). Assessing water storage changes

- 964 of Lake Poyang from multi-mission satellite data and hydrological models. Journal of
 965 Hydrology, 590, 125229.
- Xu, Y., Lin, J., Zhao, J., and Zhu, X. (2021). New method improves extraction accuracy of lake water
 bodies in Central Asia. Journal of Hydrology, 603, 127180.
- 968 Xu, F., Zhang, G., Yi, S., and Chen, W. (2022a). Seasonal trends and cycles of lake-level variations
- 969 over the Tibetan Plateau using multi-sensor altimetry data. Journal of Hydrology, 604, 127251.
- 970 Xu, N., Ma, Y., Wei, Z., Huang, C., Li, G., Zheng, H., and Wang, X. H. (2022b). Satellite observed
- 971 recent rising water levels of global lakes and reservoirs. Environmental Research Letters,
- **972** 17(7), 074013.
- 973 Yao, F., Wang, J., Wang, C., and Crétaux, J. F. (2019). Constructing long-term high-frequency time
- 974 series of global lake and reservoir areas using Landsat imagery. Remote Sensing of975 Environment, 232, 111210.
- 976 Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J. F., Wada, Y., and Berge-Nguyen, M. (2023).
- 977 Satellites reveal widespread decline in global lake water storage. Science, 380(6646), 743978 749.
- 979 Yi, S., and Sun, W. (2014). Evaluation of glacier changes in high-mountain Asia based on 10 year
 980 GRACE RL05 models. Journal of Geophysical Research: Solid Earth, 119(3), 2504-2517.
- Yi S, Wang Q, Chang L, Sun W. (2016). Changes in Mountain Glaciers, Lake Levels, and Snow
 Coverage in the Tianshan Monitored by GRACE, ICESat, Altimetry, and MODIS. Remote
 Sensing. 8(10):798.
- 984 Yi, S., Song, C., Wang, Q., Wang, L., Heki, K., and Sun, W. (2017). The potential of GRACE
- gravimetry to detect the heavy rainfall-induced impoundment of a small reservoir in the upper

- 986 Y ellow R iver. Water Resources Research, 53(8), 6562-6578.
- 987 Yi, S., and Sneeuw, N. (2021). Filling the data gaps within GRACE missions using Singular Spectrum

988 Analysis. Journal of Geophysical Research: Solid Earth, 126, e2020JB021227.

- 989 Zhang, L., Yi, S., Wang, Q., Chang, L., Tang, H., and Sun, W. (2019). Evaluation of GRACE mascon
- solutions for small spatial scales and localized mass sources. Geophysical Journal
 International, 218(2), 1307-1321.
- 992 Zhang, G., Xie, H., Kang, S., Yi, D., and Ackley, S. F. (2011). Monitoring lake level changes on the

993 Tibetan Plateau using ICESat altimetry data (2003–2009). Remote Sensing of Environment,

- 994 115(7), 1733-1742.
- 995 Zhang, G., Yao, T., Shum, C. K., Yi, S., Yang, K., Xie, H., ... and Yu, J. (2017). Lake volume and
- groundwater storage variations in Tibetan Plateau's endorheic basin. Geophysical Research
 Letters, 44(11), 5550-5560
- 998 Zhang, G., Chen, W., and Xie, H. (2019). Tibetan Plateau's lake level and volume changes from
- 999 NASA's ICESat/ICESat-2 and Landsat Missions. Geophysical Research Letters, 46(22),
 1000 13107-13118.
- 2001 Zhao, G., Li, Y., Zhou, L., and Gao, H. (2022). Evaporative water loss of 1.42 million global lakes.
- 1002Nature Communications, 13(1), 3686.
- Zhang, Y, Wang N, Yang X, Mao Z. (2022a). The Dynamic Changes of Lake Issyk-Kul from 1958 to
 2020 Based on Multi-Source Satellite Data. Remote Sensing, 14, 157.
- 1005 Zhang, Y., An, C. B., Zheng, L. Y., Liu, L. Y., Zhang, W. S., Lu, C., and Zhang, Y. Z. (2023).
- 1006 Assessment of lake area in response to climate change at varying elevations: A case study of
- 1007 Mt. Tianshan, Central Asia. Science of The Total Environment, 161665.

- 1008 Zhang S, Meng L, Zhao Y, Yang X and Huang A. (2022b). The Influence of the Tibetan Plateau
- 1009 Monsoon on Summer Precipitation in Central Asia. Frontiers in Earth Science, 10:771104.
- 1010 Zhong, Y., Wang, B., Zou, C. B., Hu, B. X., Liu, Y., and Hao, Y. (2017). On the teleconnection patterns
- 1011 to precipitation in the eastern Tianshan Mountains, China. Climate Dynamics, 49, 3123-3139.