

Supplement for

An improved GRACE-derived groundwater storage anomaly (igGWSA) dataset over global land with full consideration of non-groundwater components based on current new datasets

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Text S1. Methods for estimating glacier water storage

To be consistent with TWSA data, changes in glacier volume, $dvol$, can be converted into changes in glacier water storage represented as equivalent water height (EWH), $dEWH$, through Eq. (S1):

$$dEWH = \frac{dvol \times \rho_i}{A}, \quad (S1)$$

where ρ_i and A refer to the density of ice and the area of pixel, respectively. The units for $dvol$, ρ_i , A , and $dEWH$ are m^3 , kg/m^3 , m^2 , and kg/m^2 (equiv. to mm), respectively.

Text S2. Methods for estimating permafrost water storage

Changes in permafrost water storage, ΔPM , can be indirectly estimated from changes in active layer thickness (ALT), ΔALT , by applying Eq. (S2) (Xiang et al., 2016; Zou et al., 2022).

$$\Delta PM = -\Delta ALT \left(\frac{(1-n)k\rho_i}{(1-k)\rho_w} - \varepsilon \right), \quad (S2)$$

where n is the porosity of soil and rock in the bottom of active layer and is set to $0.4352 m^3/m^3$ (same as soil porosity of perennial land ice defined in JRA-55); ρ_i and ρ_w are the density of ice and water,

respectively; k is the ice content in the permafrost with an upper limit of 20% (Zhang et al., 2008); ε is the residual water content in the increased active layer and is determined to be 7.93% (Gouttevin et al., 2012).

Text S3. Methods for estimating pixel-wise lake and reservoir water storage

The temporal resolution of GLWS is near-monthly and was resampled to monthly by using linear interpolation. The water storage data are archived lake by lake instead of grid by grid. To allow for spatial analysis, we first identified the geographical locations of all grids intersecting with a given lake or reservoir at a $0.5^\circ \times 0.5^\circ$ resolution based on the vector boundaries derived from HydroLAKES dataset. Next, pixel-wise water storage for the given lake or reservoir can be obtained through Eq. (S3).

$$V_i = V_{total} \times \frac{A_i}{A_{total}}, \quad (S3)$$

where V_{total} and A_{total} are the total water storage and area of the lake or reservoir, respectively; V_i and A_i are the allocated water storage and intersecting area of the i th grid, respectively.

Text S4. Data processing of multi-source RZSM simulations

The stratification of root zone is 0–100 cm for GLDAS CLSM and MERRA-2; 0–10 cm, 10–40 cm, and 40–100 cm for GLDAS Noah and FLDAS Noah; and 0–7 cm, 7–28 cm, and 28–100 cm for ERA5-Land. In terms of unit, RZSM is represented as water storage (kg/m^2 , equiv. to mm) in GLDAS Noah and GLDAS CLSM, volumetric water content (m^3/m^3) in FLDAS Noah and ERA5-Land, and relative moisture (%) in MERRA-2. To be comparable with PSM, RZSM should be quantified by water storage consistently. To this end, RZSM for GLDAS Noah and GLDAS CLSM was determined as the summation of water storage in different layers. As for FLDAS Noah and ERA5-Land, RZSM can be obtained through Eq. (S4) with FLDAS Noah as an example.

$$RZSM_{FLDAS} = \sum_{k=1}^K \theta_k \times d_k, \quad (S4)$$

where θ_k and d_k are the volumetric water content and thickness of the k th layer, respectively. K is the total number of soil layers. As for MERRA-2, relative soil moisture RM should first be converted into volumetric water content by multiplying by soil porosity p derived from CLSM. $RZSM_{MERRA-2}$

was then calculated as the product of volumetric water content and root zone depth (100 cm), as shown in Eq. (S5).

$$RZSM_{MERRA-2} = RM \times p \times 100 , \quad (S5)$$

Text S5. Methods for obtaining ensemble estimation through BTCH

Taking RZSM as an example, the ensemble estimation $RZSM_{Ensemble}$ can be obtained through Eq. (S6) and Eq. (S7).

$$RZSM_{Ensemble} = w_1 \times RZSM_1 + w_2 \times RZSM_2 + \dots + w_N \times RZSM_N , \quad (S6)$$

$$w_n = \frac{\prod_{i=1, i \neq n}^N \sigma_i^2}{\sum_{n=1}^N \left(\prod_{i=1, i \neq n}^N \sigma_i^2 \right)} , \quad (S7)$$

where N is the total number of datasets to be integrated ($N=5$ for RZSM); w_n is the weight of the n th dataset; σ_i is the error variance of the i th dataset.

Text S6. Evaluation metrics of RF models

$$R^2 = 1 - \frac{\sum_{i=1}^N (PSM_{obs_i} - PSM_{pre_i})^2}{\sum_{i=1}^N (PSM_{obs_i} - \overline{PSM_{obs}})^2} , \quad (S8)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (PSM_{obs_i} - PSM_{pre_i})^2} , \quad (S9)$$

$$rRMSE = \frac{RMSE}{\overline{PSM_{obs}}} \times 100\% , \quad (S10)$$

where PSM_{obs_i} is the i th PSM value simulated by CLSM; PSM_{pre_i} is the i th PSM value predicted by RF; $\overline{PSM_{obs}}$ is the average of all PSM_{obs_i} . Higher R^2 and lower rRMSE indicate greater explanatory power and accuracy of the RF model.

Text S7. Component contribution ratio

To quantify the contribution of a given individual storage component to the interannual variability of TWS, the component contribution ratio (CCR) proposed by Kim et al. (2009) was employed, as shown in Eq. (S11) and Eq. (S12).

$$78 \quad MAD_S = \frac{1}{N} \sum_{t=1}^N |S_t - \bar{S}| , \quad (S11)$$

$$79 \quad CCR_S = \frac{MAD_S}{\sum_{S=1}^M MAD_S} \times 100\% , \quad (S12)$$

80 where MAD_S denotes the mean absolute deviation (MAD) of an individual storage component S (e.g.,
81 canopy water storage); $\bar{S}$ is the long-term mean of S during the study period; N is the number of
82 years; M is the number of storage components.

Table S1. Consideration of non-groundwater components in previous studies.

Reference	Study area	glaciers	permafrost	lakes and reservoirs	surface runoff	snow	canopy water	soil moisture
Yi et al. (2016)	China	×	×	×	×	×	×	✓
Lv et al. (2021)	China	×	×	×	×	✓	✓	✓
Zhao et al. (2023)	China	×	×	×	×	✓	✓	✓
Lin et al. (2020)	Lhasa River Basin	×	×	×	×	✓	×	✓
Zhu and Zhang (2022)	Yangtze River Basin, Yellow River Basin	×	×	×	×	✓	✓	✓
Liu et al. (2023)	northwest China	×	×	✓	✓	✓	✓	✓
Peng et al. (2021)	Central Asia	×	×	×	×	✓	✓	✓
Forootan et al. (2017)	the Middle East	×	×	✓	×	✓	✓	✓
Nikraftar et al. (2024)	the Middle East	×	×	×	✓	✓	×	✓
Shin et al. (2021)	Nepal	×	×	×	✓	✓	✓	✓
Montecino et al. (2016)	Northern Chile	×	×	×	×	✓	×	✓
Sproles et al. (2015)	Canada	×	×	✓	×	✓	×	✓
Zhu et al. (2022)	Canada	×	×	×	×	✓	×	✓

Table S1 (continued). Consideration of non-groundwater components in previous studies.

Reference	Study area	glaciers	permafrost	lakes and reservoirs	surface runoff	snow	canopy water	soil moisture
Muskett and Romanovsky (2011)	Alaska	×	×	×	✓	×	×	×
Wang et al. (2022)	North America	×	×	✓	×	✓	×	✓
Xanke and Liesch (2022)	Euro-Mediterranean region	×	×	×	✓	✓	×	✓
Muskett and Romanovsky (2009)	Arctic	×	×	×	✓	×	×	×
Lin et al. (2022)	Arctic	×	×	×	✓	✓	×	✓
Jin and Feng (2013)	Global	×	×	×	✓	✓	✓	✓
Xiang et al. (2016)	Tibetan Plateau	✓	✓	✓	×	✓	×	✓
Zhang et al. (2017)	Tibetan Plateau	✓	✓	✓	×	✓	×	✓
Zou et al. (2022)	Tibetan Plateau	✓	✓	✓	×	✓	×	✓
Fan et al. (2023)	northern Himalayas	✓	✓	✓	×	✓	×	✓
Li et al. (2023)	China	✓	×	✓	✓	✓	✓	✓
Liu et al. (2020)	Asia and eastern Europe	✓	×	✓	×	✓	✓	✓
Wang et al. (2018)	global endorheic basins	✓	×	✓	×	✓	✓	✓

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Table S2. Interannual trends in igGWSA, GWSA_{ignored}, and GlacierWSA in glacier-covered regions.

Region	igGWSA	GWSA _{ignored}	GlacierWSA	Region	igGWSA	GWSA _{ignored}	GlacierWSA
Global	-0.19**	-4.03**	-3.85**	Region 10	0.58**	0.30**	-0.28**
Region 1	4.92**	-8.87**	-13.79**	Region 11	1.40**	-0.07	-1.47**
Region 2	1.41**	0.04	-1.36**	Region 12	-0.04	-0.64**	-0.60**
Region 3	3.28**	-10.01**	-13.30**	Region 13	0.32**	-0.35**	-0.66**
Region 4	4.99**	-8.82**	-13.81**	Region 14	0.63**	-0.61**	-1.24**
Region 5	-18.79**	-24.72**	-5.92**	Region 15	0.58**	-1.53**	-2.10**
Region 6	12.49**	-7.78**	-20.27**	Region 16	0.37**	0.08	-0.29**
Region 7	7.86**	-7.16**	-15.03**	Region 17	2.25**	-2.37**	-4.62**
Region 8	1.73**	0.47*	-1.27**	Region 18	1.54**	0.15	-1.38**
Region 9	-1.42	-10.36**	-8.95**				

87 Note: Unit: cm/yr. * indicates significance at the 0.05 level. ** indicates significance at the 0.01 level.

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Table S3. Interannual trends in igGWSA, GWSA_{simplified} and LRWSA in giant lakes.

Lake	igGWSA	GWSA _{simplified}	LRWSA	Lake	igGWSA	GWSA _{simplified}	LRWSA
Global	-0.19**	-0.35**	-0.11	Malawi	2.60**	-1.32**	-3.92**
Caspian Sea	0.77*	-4.82**	-5.58**	Great Slave	-0.66*	-0.74**	-0.09
Great Lakes of NA	-1.74*	0.99**	2.72**	Winnipeg	-0.30	0.68**	0.98
Victoria	-1.45	1.56*	3.01**	Ladoga	-0.78	0.39*	1.17
Tanganyika	-0.53	0.39	0.92	Balkhash	-1.40*	-0.04	1.36*
Baikal	0.68**	-0.70**	-1.38**	Aral Sea	11.46**	-1.15**	-12.60**
Great Bear	-0.09	-0.13**	-0.03	Lakes of Tibetan Plateau	-2.31**	0.04	2.62**

95 Note: Unit: cm/yr. * indicates significance at the 0.05 level. ** indicates significance at the 0.01 level.

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Table S4. Interannual trends in igGWSA, GWSA₂₀₀ and GWSA₂₈₉ in deep-soil areas.

Region	igGWSA	GWSA ₂₀₀	GWSA ₂₈₉	Region	igGWSA	GWSA ₂₀₀	GWSA ₂₈₉
Mississippi	-0.08	-0.08	-0.03	Congo	0.06	-0.24**	0.53**
Volga	-0.24*	-0.37**	-0.16**	Songhua-Liaohe	-0.06	-0.07	0.39*
Ob	0.03	-0.06	0.22**	Pampas	-0.08	-0.16	0.69**
Loess Plateau	-0.83**	-0.99**	-0.42**	Ganges-Brahmaputra	-1.09**	-1.25**	-1.24**

98 Note: Unit: cm/yr. * indicates significance at the 0.05 level. ** indicates significance at the 0.01 level.

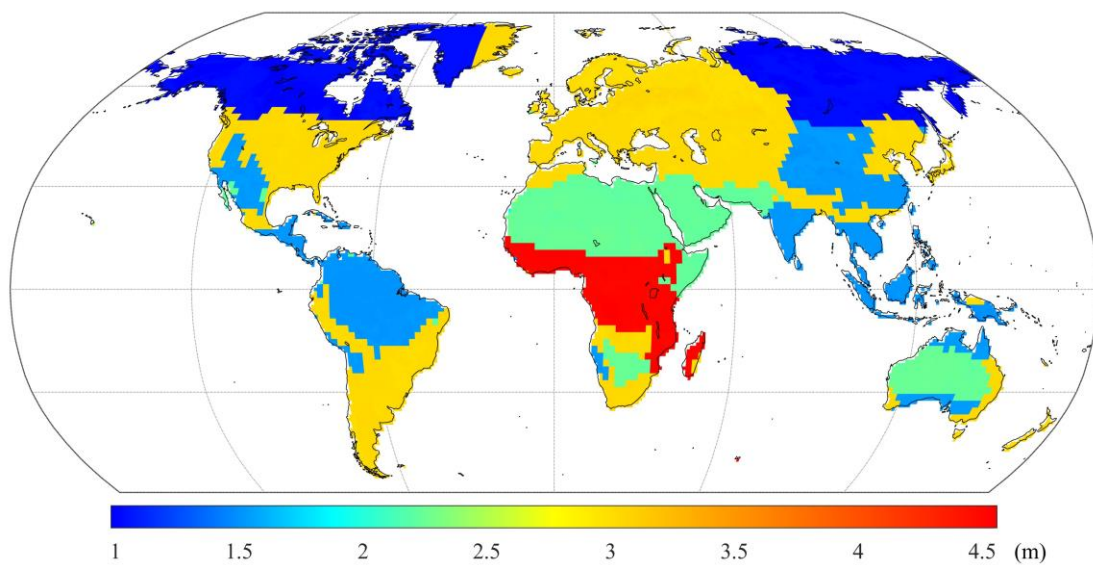


Figure S1. Soil depth information defined in GLDAS VIC model.

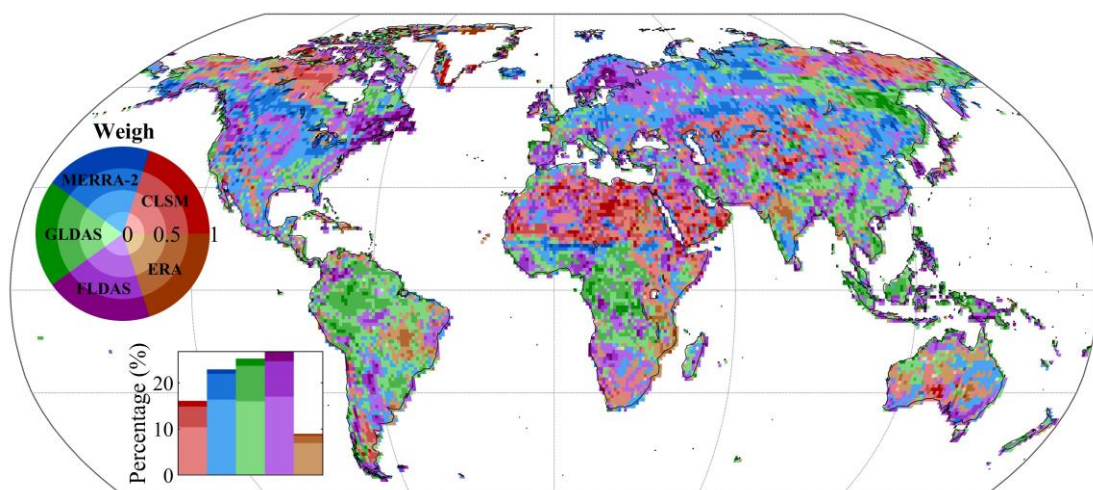


Figure S2. Map of the optimal RZSM dataset.

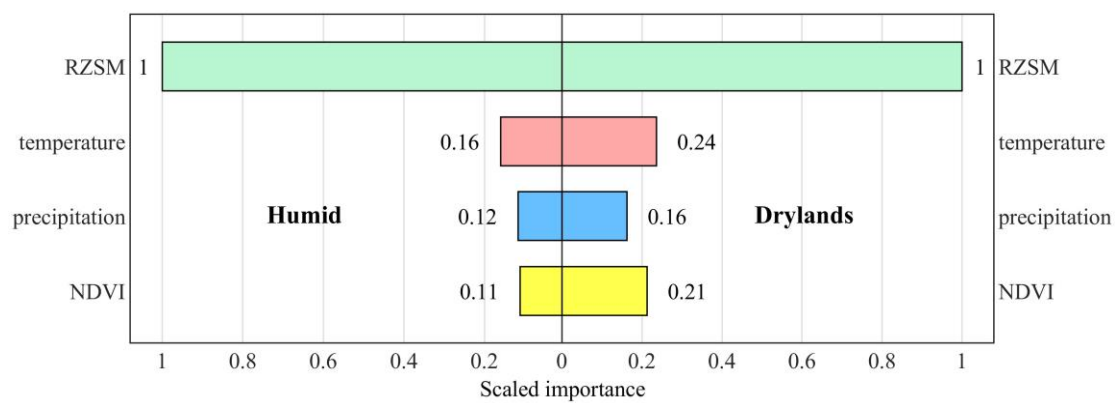


Figure S3. Scaled importance of predictor variables for PSM modelling in humid regions and drylands.
Note: Scaled importance was derived by setting the value of RZSM to 1 and proportionally scaling the values of other variables.

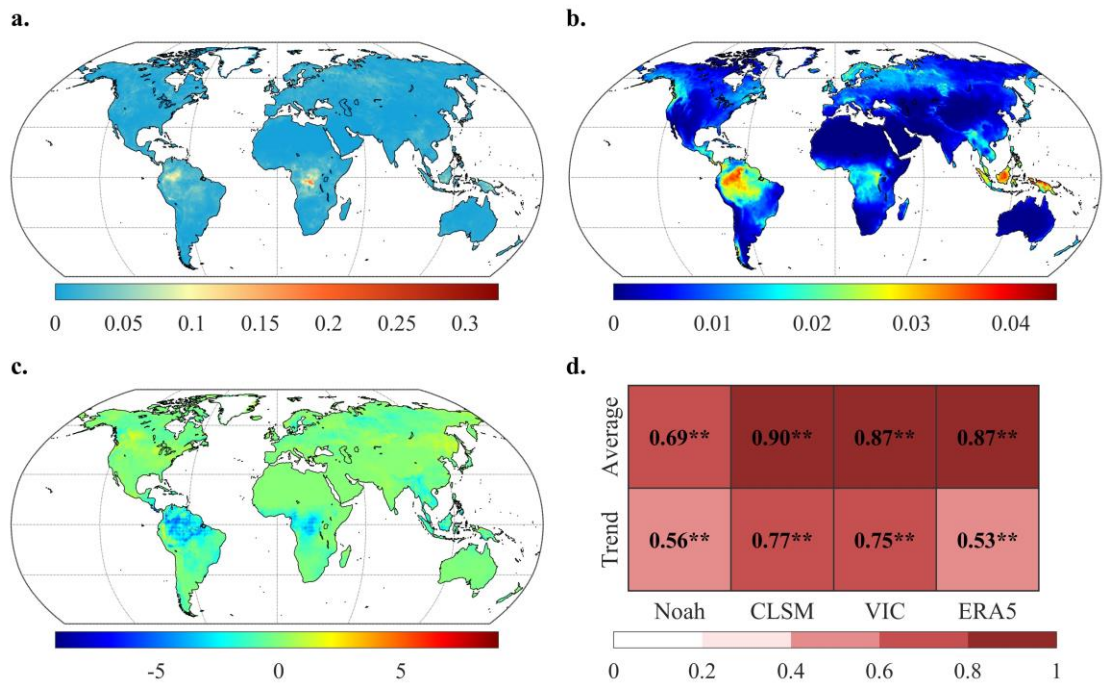


Figure S4. (a) Map of contribution ratio of canopy water storage (CWS) to TWS variability (unit: %). (b) Map of the multi-year (2000–2019) average of CWS (unit: cm). (c) Map of the interannual trend in CWS (unit: e-04 cm/yr). The three maps consistently revealed that the hotspots of CWS variability were located in tropical rainforest regions, encompassing the Amazon Basin, the Congo Basin, and Southeast Asia. The three maps were made based on the ensemble data of CWS simulations from four LSMs, i.e., GLDAS Noah, GLDAS CLSM, GLDAS VIC, and ERA5-Land. (d) The spatial Pearson's correlation coefficients between the four single-source data and the ensemble data for both multi-year average and interannual trend. ** indicates significance at the 0.01 level. The spatiotemporal patterns of CWS revealed by the four single-source data were all highly consistent with the ensemble data, indicating the high robustness of map a, b, and c.

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