

**An improved empirical framework for long-term reconstruction of terrestrial
water storage and runoff in Pan-Arctic basins**

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15 Tables S1

Text S1: Data

Precipitation and air temperature data: Accurate precipitation estimates remain challenging in northern high latitudes because of sparse gauge coverage and limited cold-season observations (Lauer et al., 2023; Zhang et al., 2013). To reduce dependence on any single dataset, we used five precipitation–air temperature dataset combinations (Table 1).

20 *Three observation-based gridded products:*

- Climatic Research Unit Time-series data (CRU; Harris et al., 2020).
https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.09/.
- Global Precipitation Climatology Centre (GPCC) Precipitation Analysis Monthly Version 2025 (Schirmeister et al., 2025). <https://www.dwd.de/EN/ourservices/gpcc/gpcc.html>. Because GPCC provides precipitation only,
25 it was paired with the Berkeley Earth Surface Temperature (BEST) dataset (Rohde and Hausfather, 2020).
<https://berkeleyearth.org/data/>.
- University of Delaware Air Temperature & Precipitation (U. Delaware; Willmott and Matsuura, 1995).
https://psl.noaa.gov/data/gridded/data.UDel_AirT_Precip.html.

Two reanalysis products:

- 30 • ERA5 monthly averaged data on single levels (ERA5 single; Hersbach et al., 2020).
<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=overview>.
- Japanese Reanalysis for Three Quarters of a Century (JRA-3Q; Kosaka et al., 2024).
https://www.data.jma.go.jp/jra/html/JRA-3Q/index_en.html.

Snow water equivalent data: We used five snow water equivalent (SWE) products (Table 2).

35 *Three reanalysis products:*

- ERA5-Land monthly averaged data (ERA5-Land; Muñoz-Sabater et al., 2021).
<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land-monthly-means?tab=overview>.
- Crocus-ERA5 snow product (Crocus-ERA5; Ramos Buarque et al., 2025). <https://zenodo.org/records/14513248>.
- JRA-3Q

40 *One global hydrological model product:*

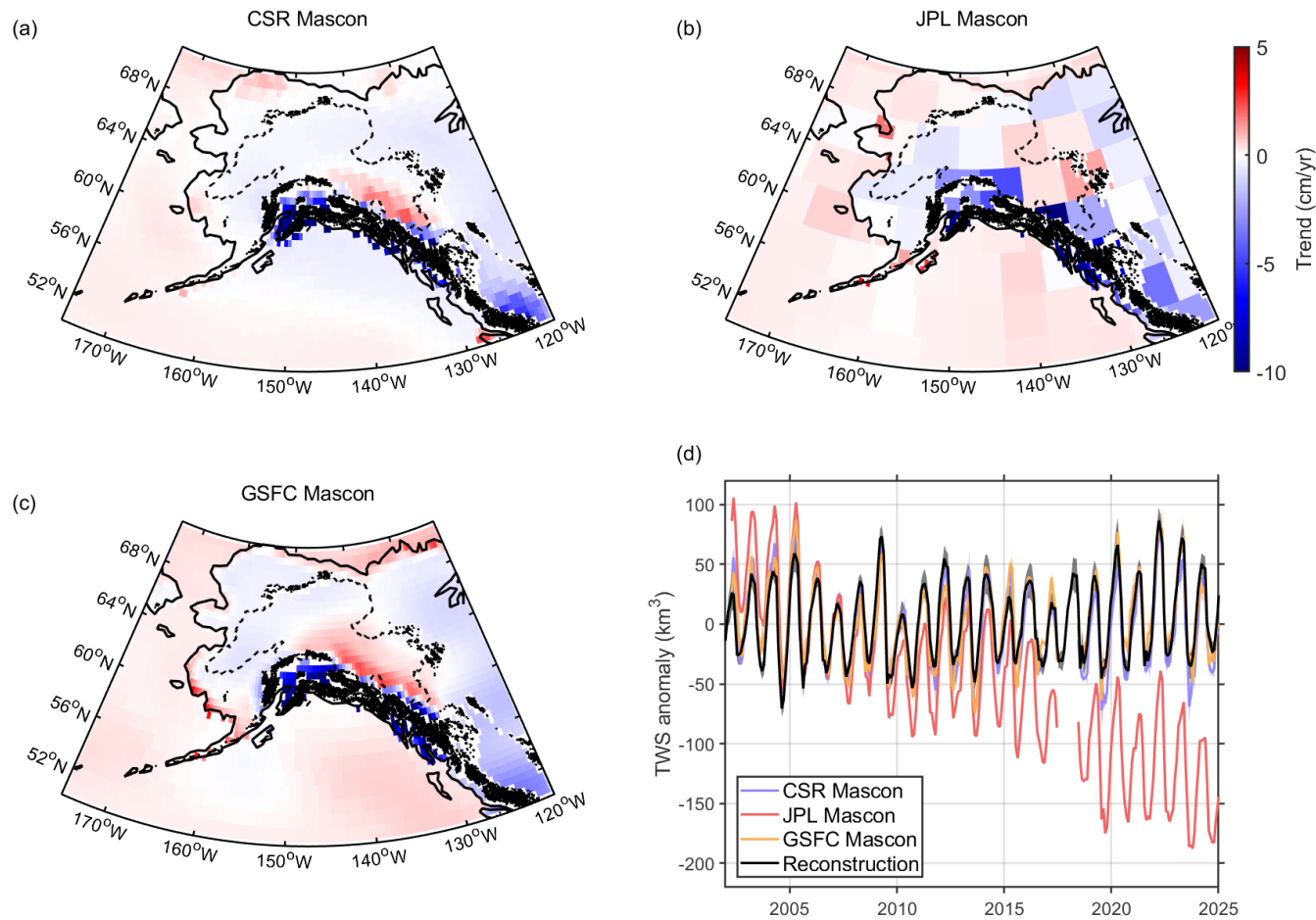
- WaterGAP version 2.2e 20crv3-w5e5 product (Müller Schmied et al., 2024). <https://gude.uni-frankfurt.de/collections/61f471df-7fda-478a-a7f5-6d8ae9be0f5d>.

One land surface model product:

- 45 • Global Land Data Assimilation System Noah Land Surface Model v2.0 (GLDAS NOAH; Rodell et al., 2004).
<https://ldas.gsfc.nasa.gov/gldas>.

Snow cover fraction data: We used two snow cover fraction products (Table 3).

- ERA5-Land.
- Crocus-ERA5.



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51 **Figure S1.** TWS trends in and around the Yukon basin derived from different GRACE (-FO) mascon products. (a–c) Spatial TWS trends over April 2002–
 52 December 2025 from the CSR (a), JPL (b), and GSFC (c) mascon products, respectively. Black symbols indicate glacier locations identified from the Randolph
 53 Glacier Inventory 7.0. The dashed boundary delineates the Pilot Station catchment in the Yukon basin (ID 11). (d) Comparison of reconstructed TWS with TWS
 54 estimates from the three GRACE (-FO) mascon products for the Pilot Station catchment after excluding 0.5° grid cells containing glaciers. Gray shading indicates
 55 reconstruction uncertainty.

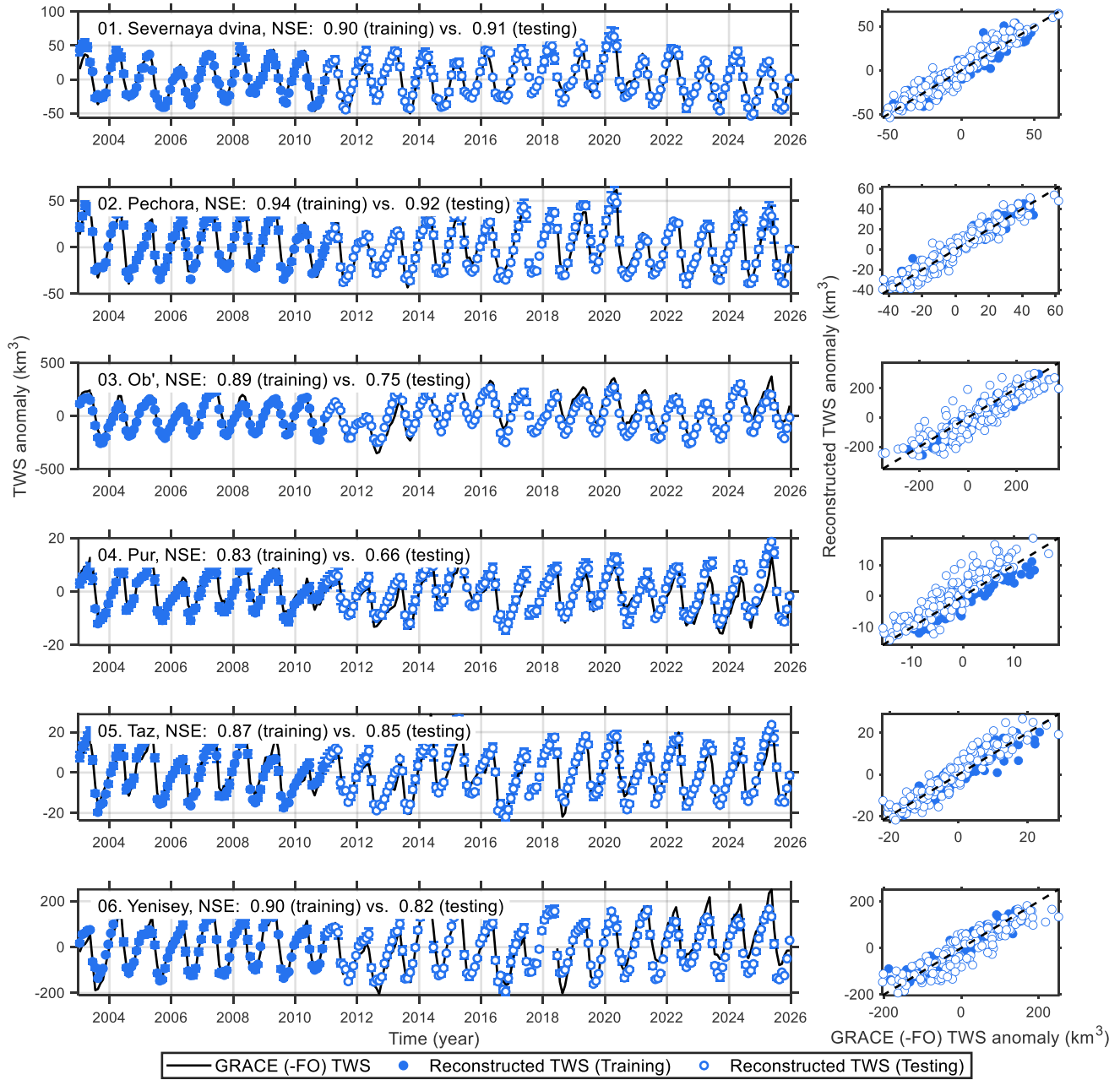
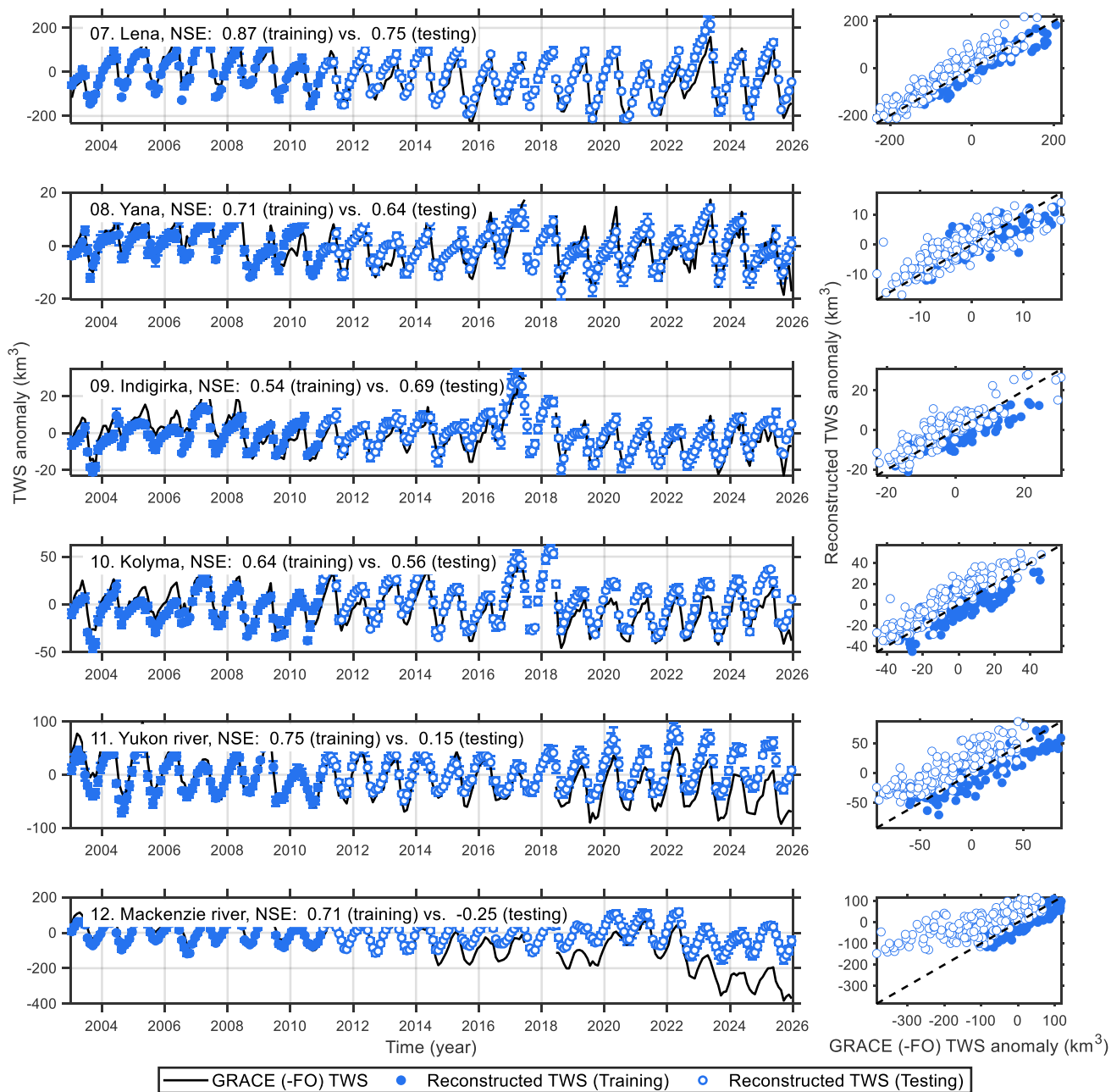


Figure S2. Training and testing evaluation of reconstructed TWS against GRACE (-FO) observations for the 12 study catchments. The mean TWS time series from the CSR, JPL, and GSFC mascon products was used as the reference. Filled blue circles indicate the training period from 2003 to 2010, which was also used for parameter estimation, whereas open blue circles indicate the testing period from 2011 to 2025, excluding the approximately 1-year data gap between GRACE and GRACE-FO. The left panels show the TWS time series, with Nash–Sutcliffe efficiency (NSE) values for the training and testing periods indicated in each panel. The right panels show the corresponding scatterplots between reconstructed and reference TWS, with the dashed line indicating the 1:1 relationship. Blue error bars indicate reconstruction uncertainty.



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65 **Figure S2. (continued).**

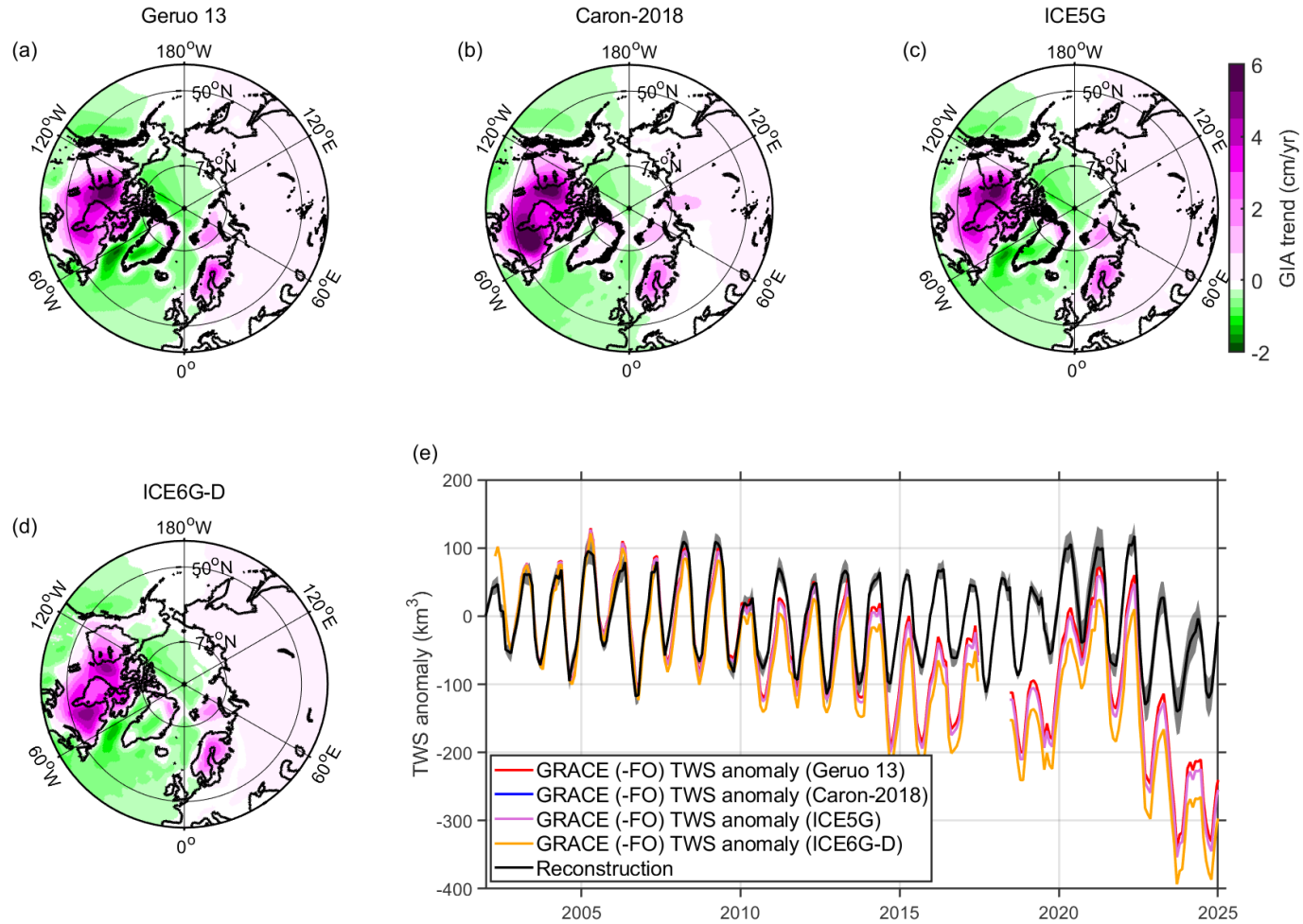


Figure S3. Sensitivity of GRACE and GRACE-FO TWS estimates in the Mackenzie basin to different glacial isostatic adjustment (GIA) corrections. (a–d) Spatial patterns of GIA-induced equivalent water height trends from the Geruo13 (A et al., 2013), Caron-2018 (Caron et al., 2018), ICE-5G (Argus and Peltier, 2010), and ICE-6G-D (Peltier et al., 2015) models, respectively. (e) Comparison of reconstructed TWS with GRACE and GRACE-FO TWS estimates after applying the four GIA corrections in the Mackenzie basin. Gray shading indicates reconstruction uncertainty.

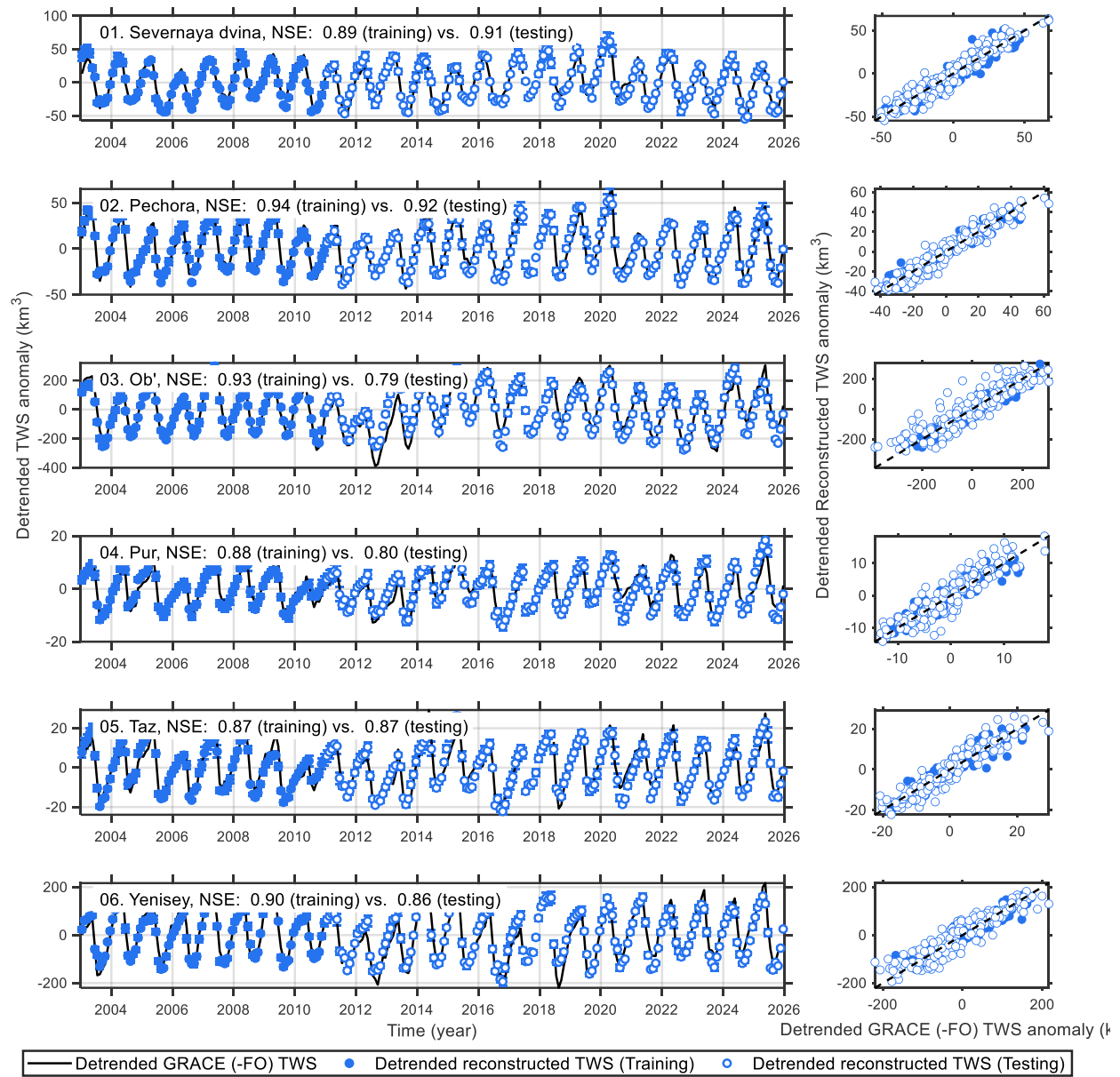


Figure S4. Training and testing evaluation of detrended reconstructed TWS against detrended GRACE (-FO) TWS observations for the 12 Pan-Arctic catchments. The mean TWS time series from the CSR, JPL, and GSFC mascon products was used as the reference. Filled blue circles indicate the training period from 2003 to 2010, which was also used for parameter estimation, whereas open blue circles indicate the testing period from 2011 to 2025, excluding the approximately 1-year data gap between GRACE and GRACE-FO. Linear trends were removed from both reconstructed and reference TWS before evaluation. The left panels show the detrended TWS time series, with Nash–Sutcliffe efficiency (NSE) values for the training and testing periods indicated in each panel. The right panels show the corresponding scatterplots between detrended reconstructed and reference TWS, with the dashed line indicating the 1:1 relationship. Blue error bars indicate reconstruction uncertainty.

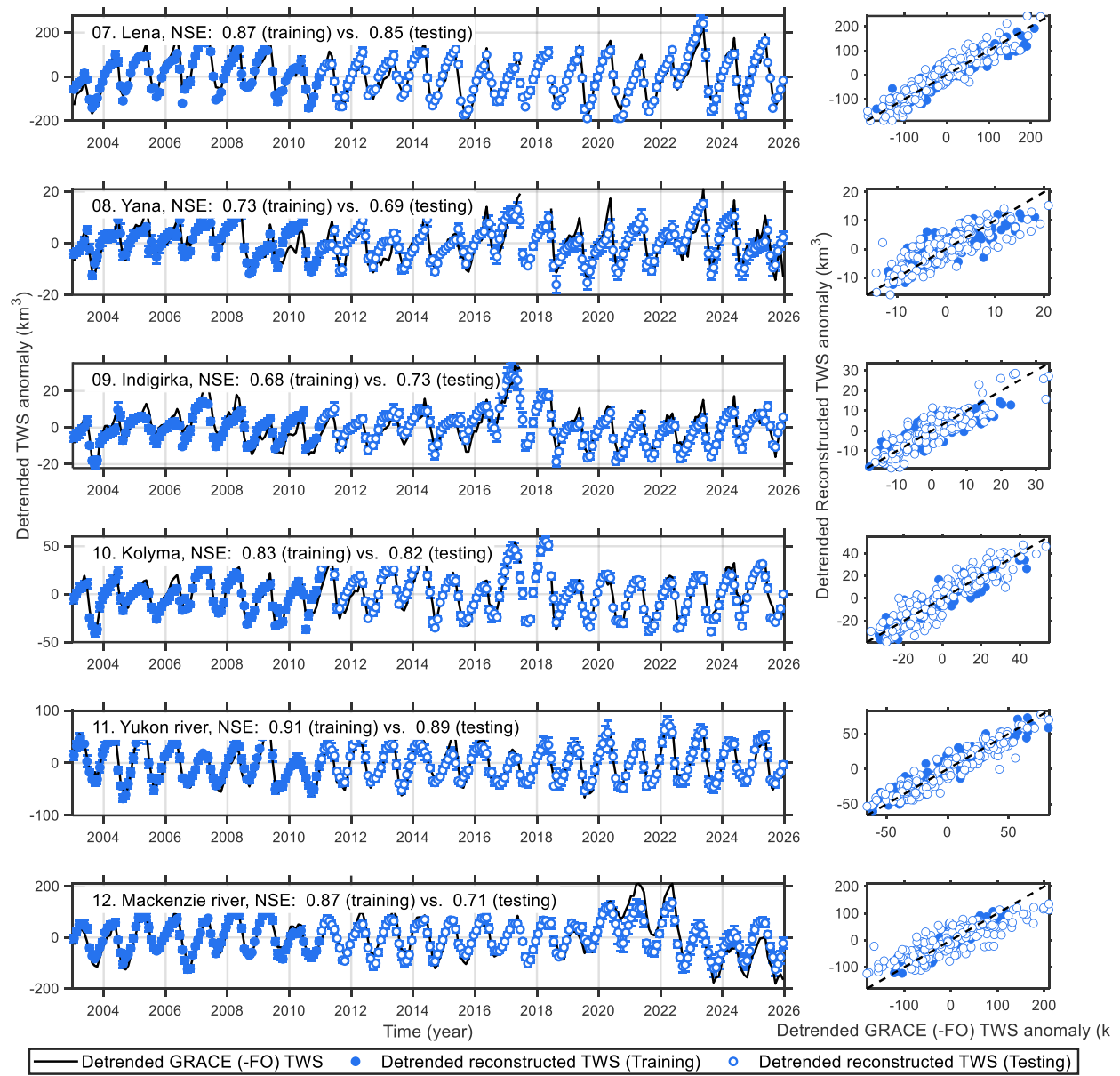


Figure S4. (continued).

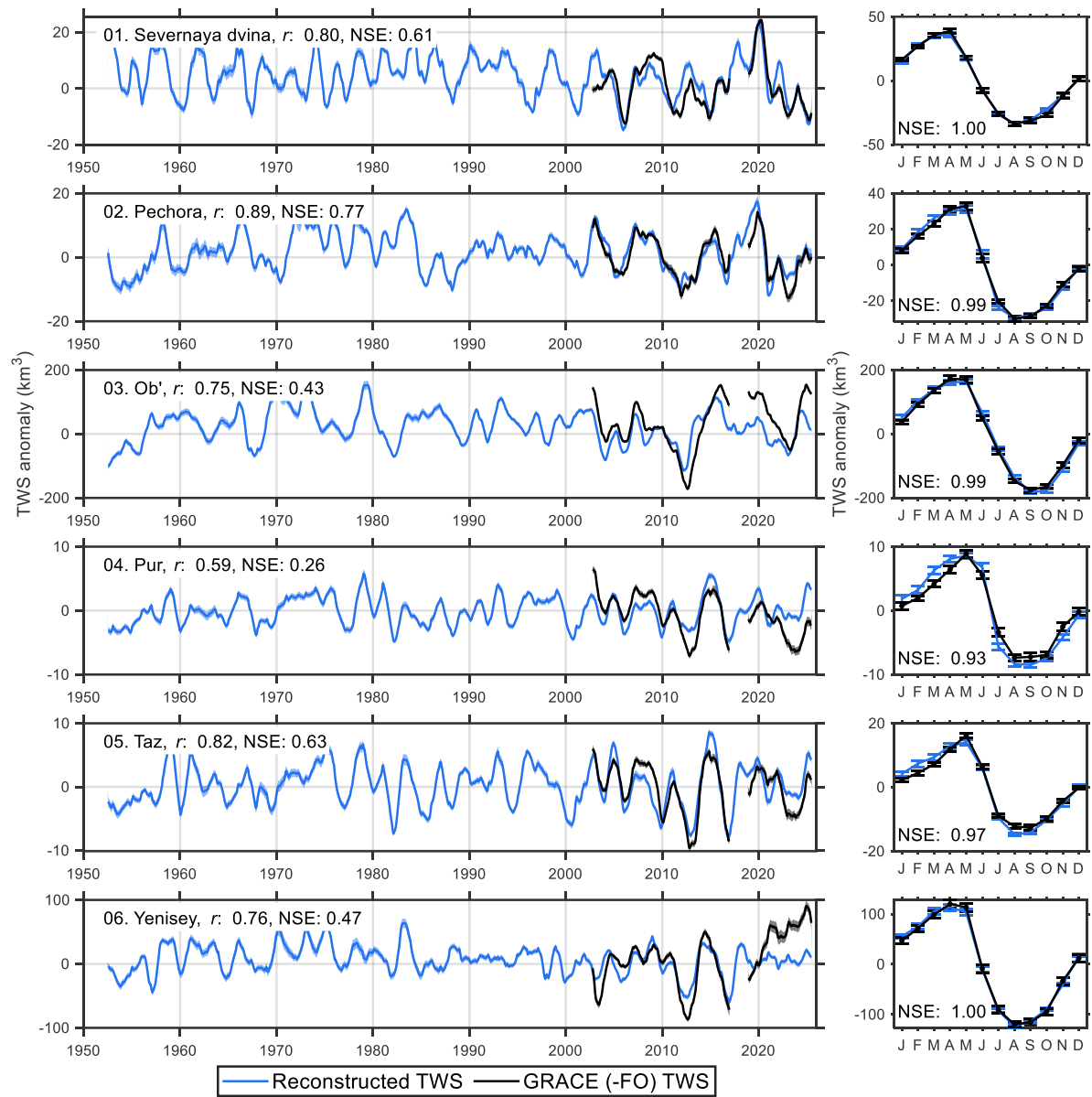
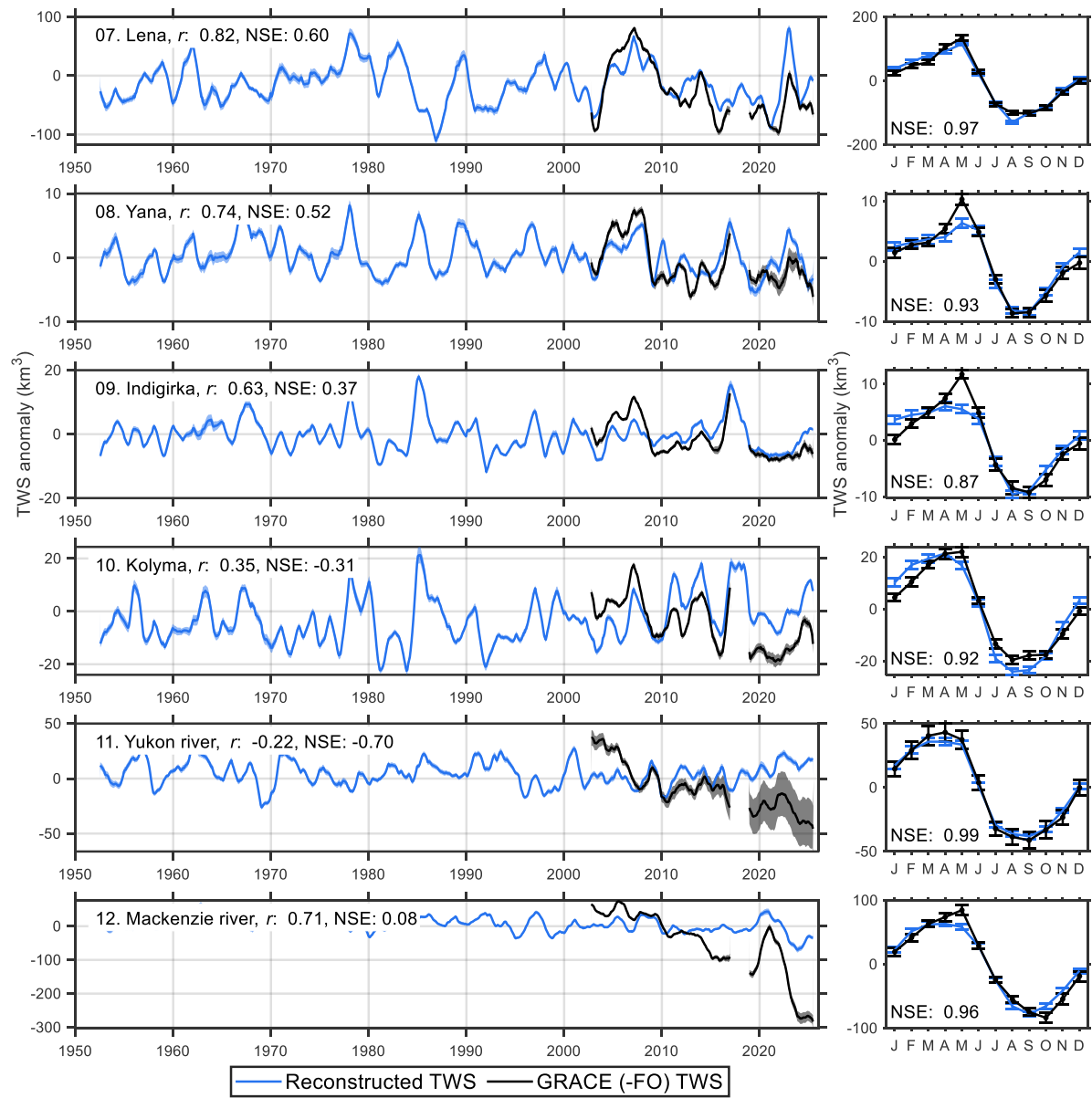


Figure S5. Comparison of reconstructed TWS with GRACE and GRACE-FO observations for the 12 Pan-Arctic catchments. The left panels show the non-seasonal component after applying a 1-year sliding window, with the corresponding correlation coefficient (r) and Nash–Sutcliffe efficiency (NSE) indicated in each panel. The right panels show the mean seasonal cycle, with the corresponding NSE indicated in each panel. Error bars and shading indicate uncertainty.



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90 **Figure S5. (continued).**

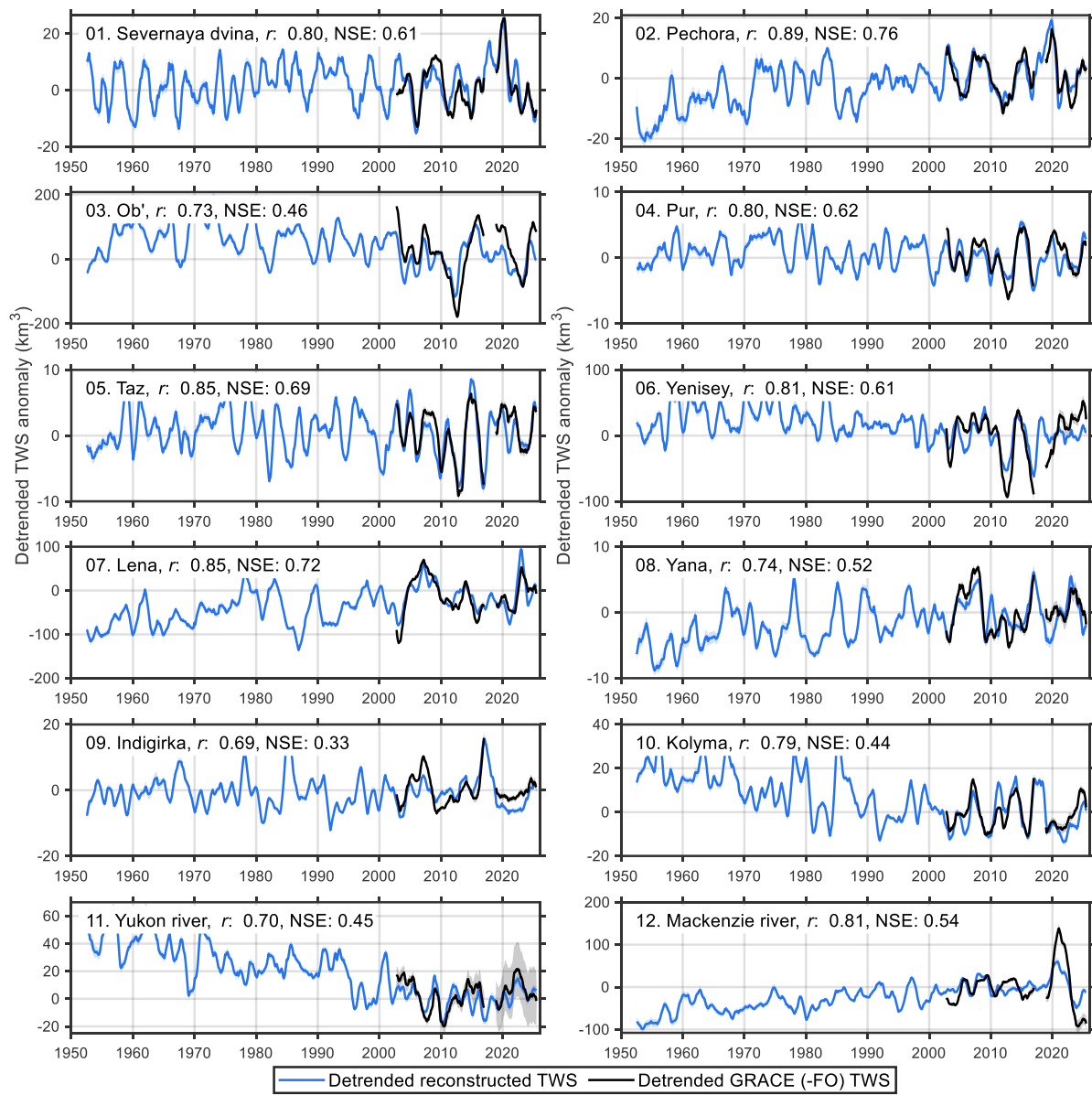


Figure S6. Comparison of detrended non-seasonal TWS components from the reconstruction and GRACE (-FO) observations for the 12 Pan-Arctic catchments. The non-seasonal components were processed using a 1-year sliding window, and linear trends were subsequently removed from both reconstructed and reference TWS before evaluation. The corresponding correlation coefficient (r) and Nash–Sutcliffe efficiency (NSE) are shown in each panel.

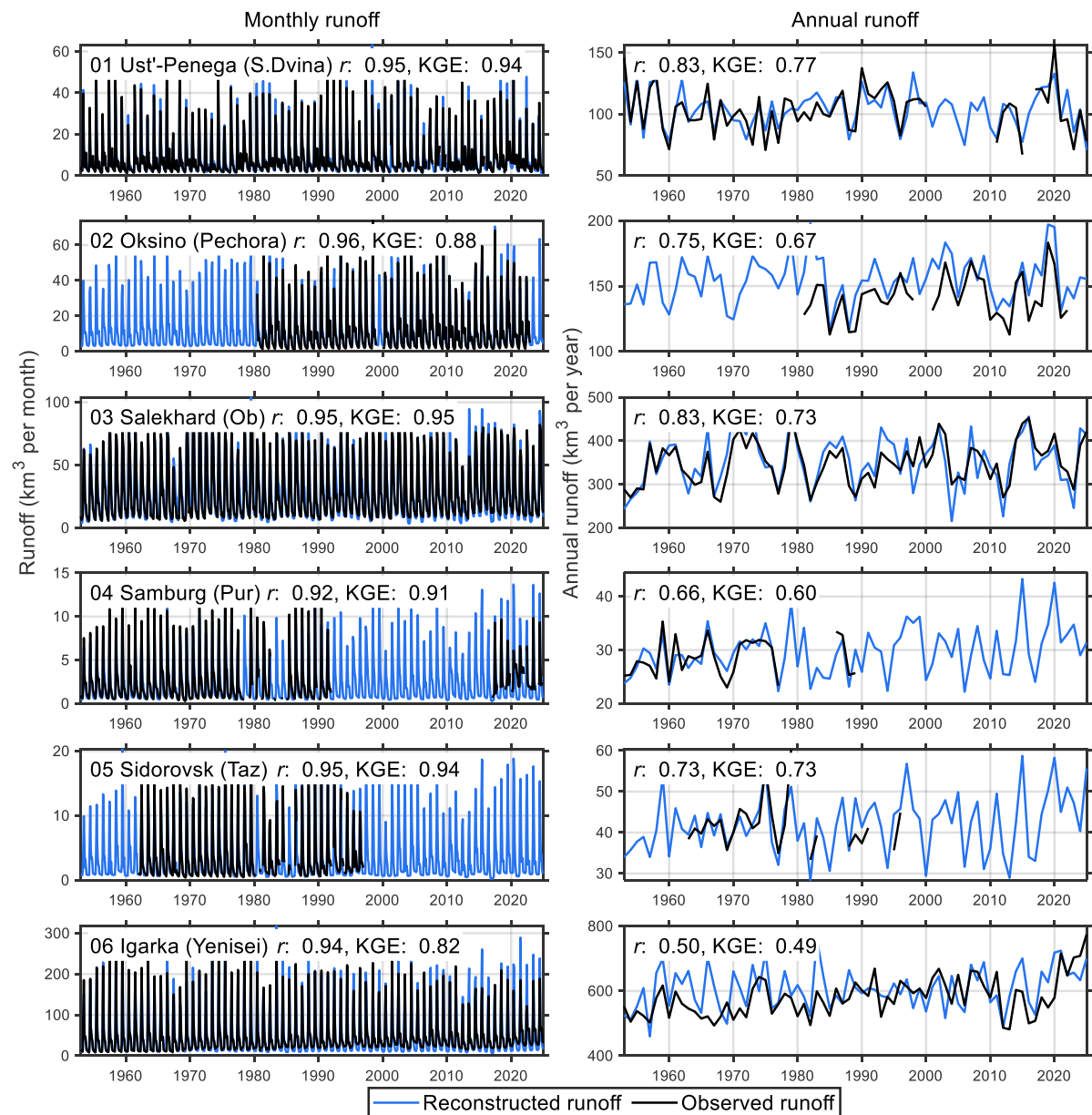


Figure S7. Comparison of reconstructed and observed runoff at the 12 Pan-Arctic gauging stations. Runoff was reconstructed using the TWS developed in this study and the refined runoff–TWS relationship. The left column shows monthly runoff time series, and the right column shows annual runoff calculated for hydrological years from September to August. The correlation coefficient (r) and Kling–Gupta efficiency (KGE) were calculated over periods with available gauge observations and are shown in each panel.

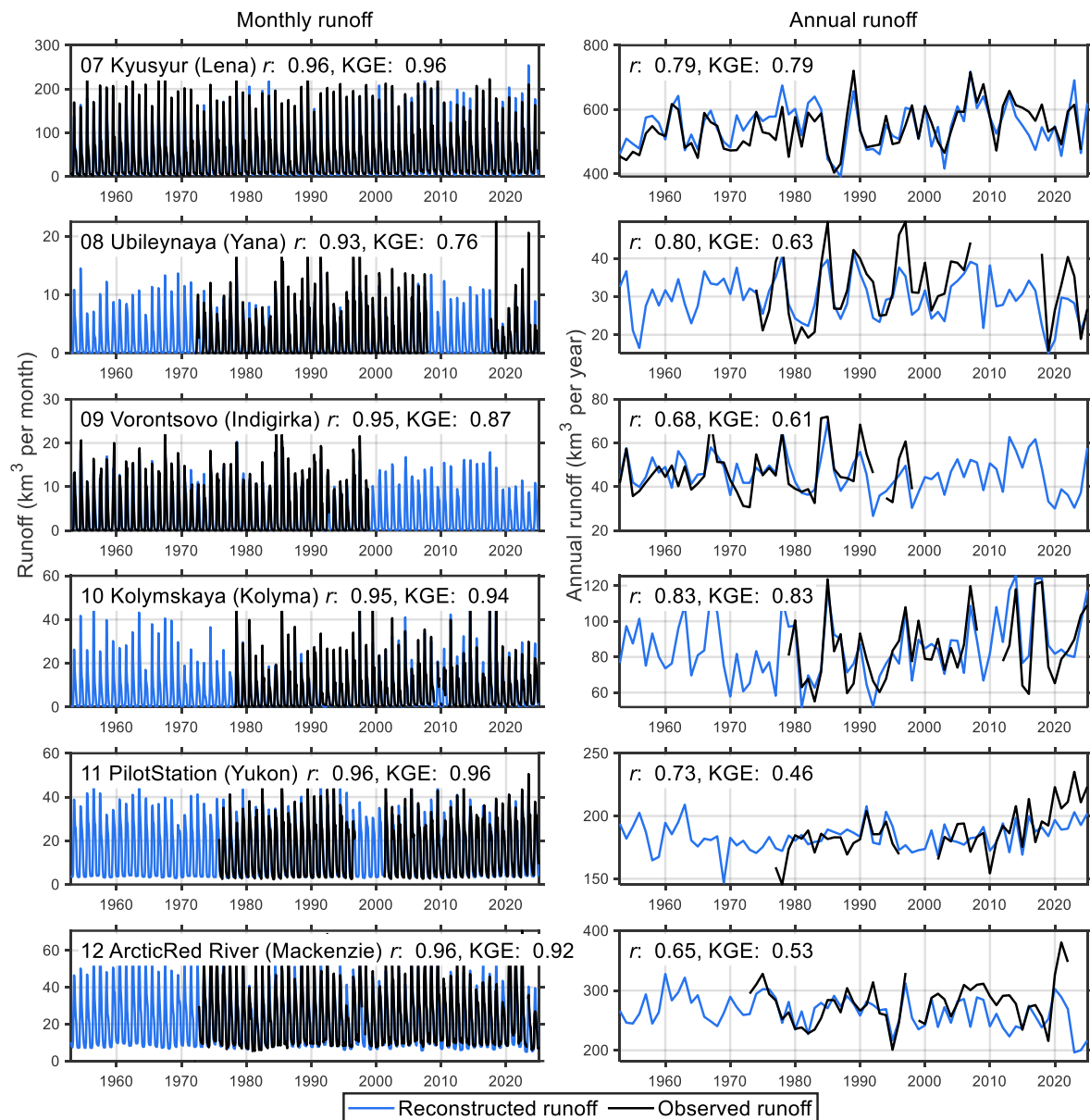


Figure S7. (continued).

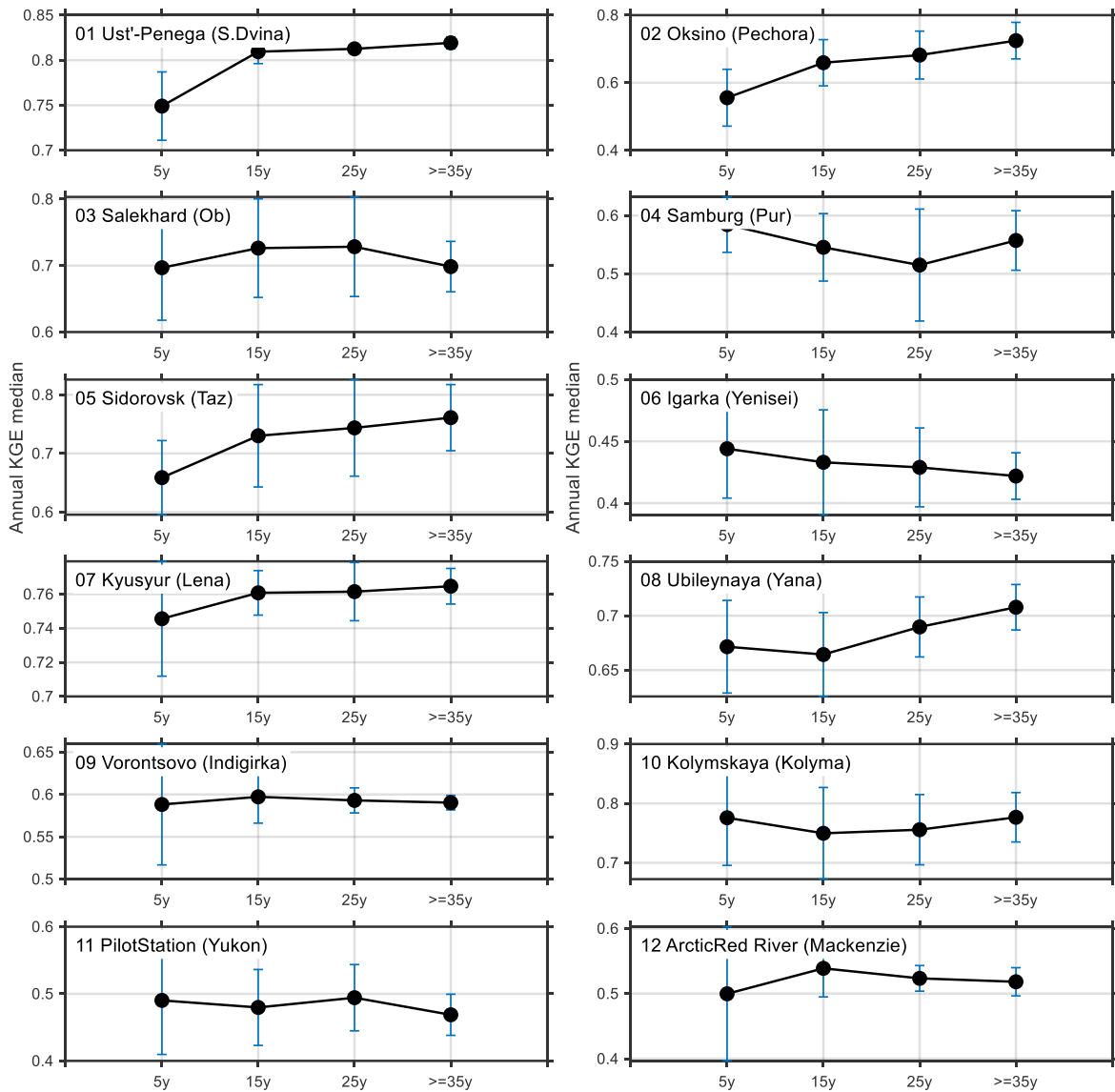


Figure S8. Sensitivity of annual runoff reconstruction to the length of the parameter-estimation window in the refined runoff–TWS relationship. For each gauging station and each window-length category, black circles indicate the median annual Kling–Gupta efficiency (KGE) across all available parameter-estimation periods, and error bars indicate the corresponding standard deviations. Parameter-estimation windows of 35 years and longer were grouped into the ≥ 35 -year category.

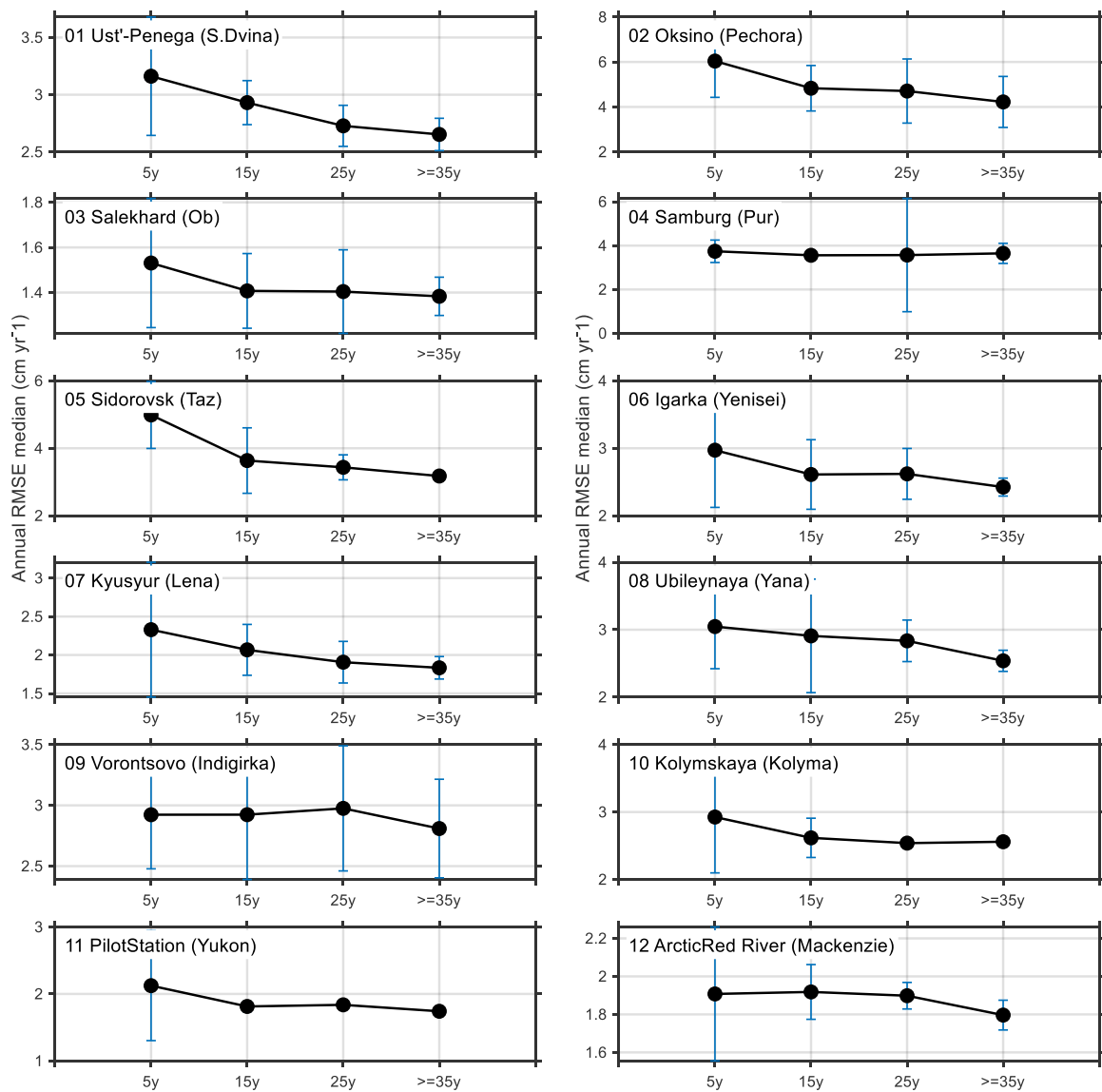


Figure S9. Sensitivity of annual runoff reconstruction to the length of the parameter-estimation window in the refined runoff–TWS relationship. For each gauging station and each window-length category, black circles indicate the median annual root mean square error (RMSE) across all available parameter-estimation periods, and error bars indicate the corresponding standard deviations. Parameter-estimation windows of 35 years and longer were grouped into the ≥ 35 -year category.

116 **Table S1.** Acronyms that Involved in this Paper

ArcticGRO	Arctic Great Rivers Observatory
BEST	Berkeley Earth Surface Temperatures gridded dataset
CRU	Climatic Research Unit Time-series data
CSR	Center for Space Research
ERA5-Land	ERA5-Land monthly averaged data
ERA5 single	ERA5 monthly averaged data on single levels
ET	EvapoTranspiration
GHM	Global Hydrological Model
GIA	Glacial Isostatic Adjustment
GLDAS NOAH	Global Land Data Assimilation System Noah Land Surface Model v2.0
GPCC	Global Precipitation Climatology Centre Precipitation Analysis Monthly
GRACE	Gravity Recovery and Climate Experiment satellite
GRACE-FO	GRACE Follow-On
GRDC	Global Runoff Data Centre
GSFC	Goddard Space Flight Center
JPL	Jet Propulsion Laboratory
JRA-3Q	Japanese Reanalysis for Three Quarters of a Century
KGE	Kling–Gupta Efficiency
LSM	Land Surface Models
MCMC	Markov chain Monte Carlo
NSE	Nash–Sutcliffe Efficiency
SWE	Snow Water Equivalent
TWS	Terrestrial Water Storage
U. Delaware	University of Delaware Air Temperature & Precipitation
WaterGAP 20crv3-w5e5	WaterGAP version 2.2e 20crv3-w5e5

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