Supporting Information for "Coherent streamflow variability in Monsoon Asia over the past eight centuries—links to oceanic drivers"

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Introduction

In this Supporting Information, we provide some information on previous reconstruction works in Monsoon Asia, and more details on data: streamflow station metadata, streamflow preprocessing, and MADA's starting year. We also provide a comparison of spatial coherence in the modern period, and a more in-depth analysis of the streamflow–SST teleconnection. Finally we provide additional results to support the findings in the main text.

Text S1. Previous streamflow reconstructions in Monsoon Asia

The first streamflow reconstruction in Monsoon Asia was by Davi et al. (2006). Since then, 27 reconstruction studies have appeared, more than half of which were published in the last four years (Figure S1). Each of these works studied a specific river; most of them focused on China (Table S1).

Text S2. Station selection

We obtained most of our mean annual flow data from the Global Streamflow Indices and Metadata (GSIM) Archive (Do et al., 2018; Gudmundsson et al., 2018). The GSIM authors ignored missing data when calculating mean annual flow, but provided for each station the fraction of missing days for the whole record length, and the number of missing days for each year. We first selected stations with no more than 3% of missing days over the whole record length. Then, for each of these stations, we looked at each year's number of missing days, and if this number was greater than 30, we considered that year's data as missing. We adopted these criteria to avoid the situation where the mean annual flow was calculated from too many missing data. After this second step, we counted the number of non-missing years for each station, and retain only those having at least 41 years.

For the Chao Phraya, we obtained monthly flow from the Thai Royal Irrigation Department (`hydro-1.net`, in Thai) for stations P.1, N.1, and C.2, and calculated the mean annual flow from the monthly flow. If there were more than one month missing for any year, that year was considered missing as well (similar to what we did with the GSIM stations).

For Mekong, Yangtze, Citarum, and Brahmaputra data, we obtained annual flow directly from our colleagues, and we did not have any information on the degree of missingness.

There were no missing data in South Korea, but the longest record was only 39 years. We wanted to have a station for this country, so we made an exception for the 41-year criterion. Similarly, we made an exception to the Yeruu River: the mean annual flow here is 49.8 m^3/s, slightly less than the 50 m^3/s threshold, but we retain this record so as to have a station in Mongolia.

Text S3. Streamflow data preprocessing

We determined the degree of asymmetry of the streamflow data using the Hinkley's D statistic (Hinkley, 1977), formulated according to equation (1)

$$D = \frac{m - \mu}{q} \tag{1}$$

where m is the sample median, μ the sample mean, and q the sample inter-quartile range. If log-transforming reduces the absolute value of D for a station, then we will use the log-transformed flow as reconstruction target; otherwise we use the untransformed flow. We also check the densities of the transformed and untransformed flow visually (Figure S3), and found that the densities are similar for most stations.

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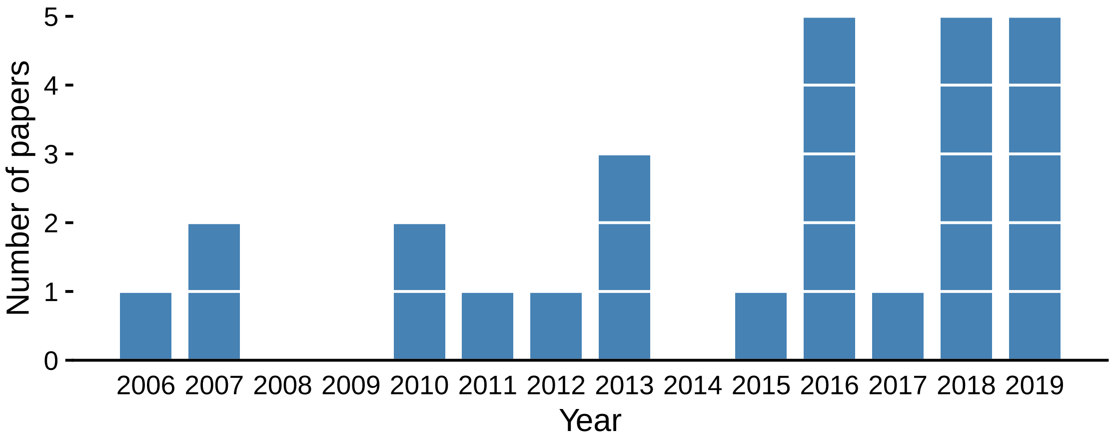

Figure S1. Number of Monsoon Asia streamflow reconstruction papers published each year till September 2019. The publications are listed in Table S1.

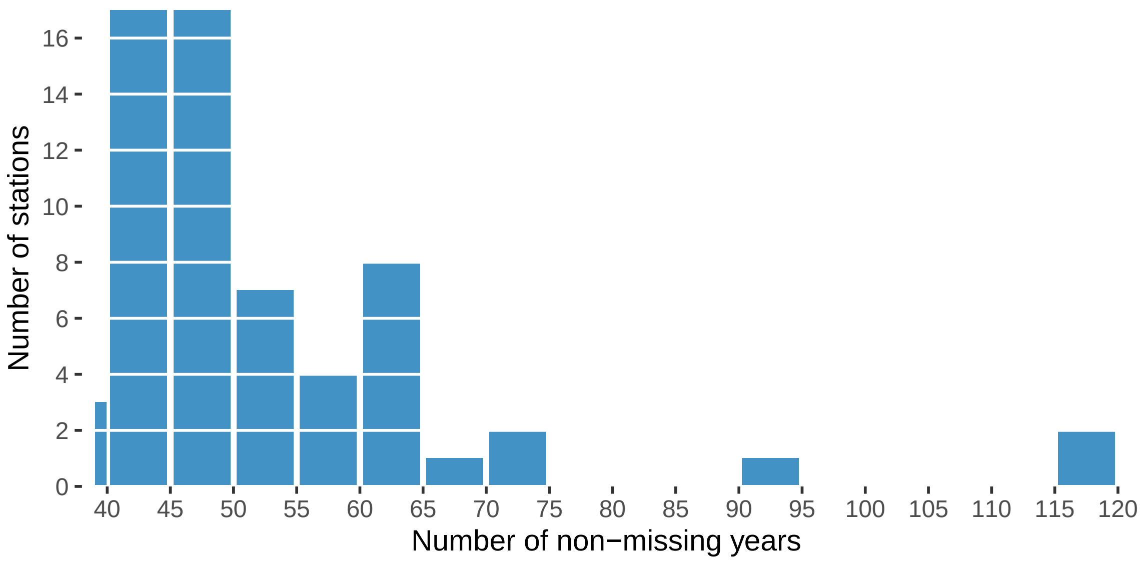

Figure S2. Distribution of the number of non-missing years of the streamflow data set.

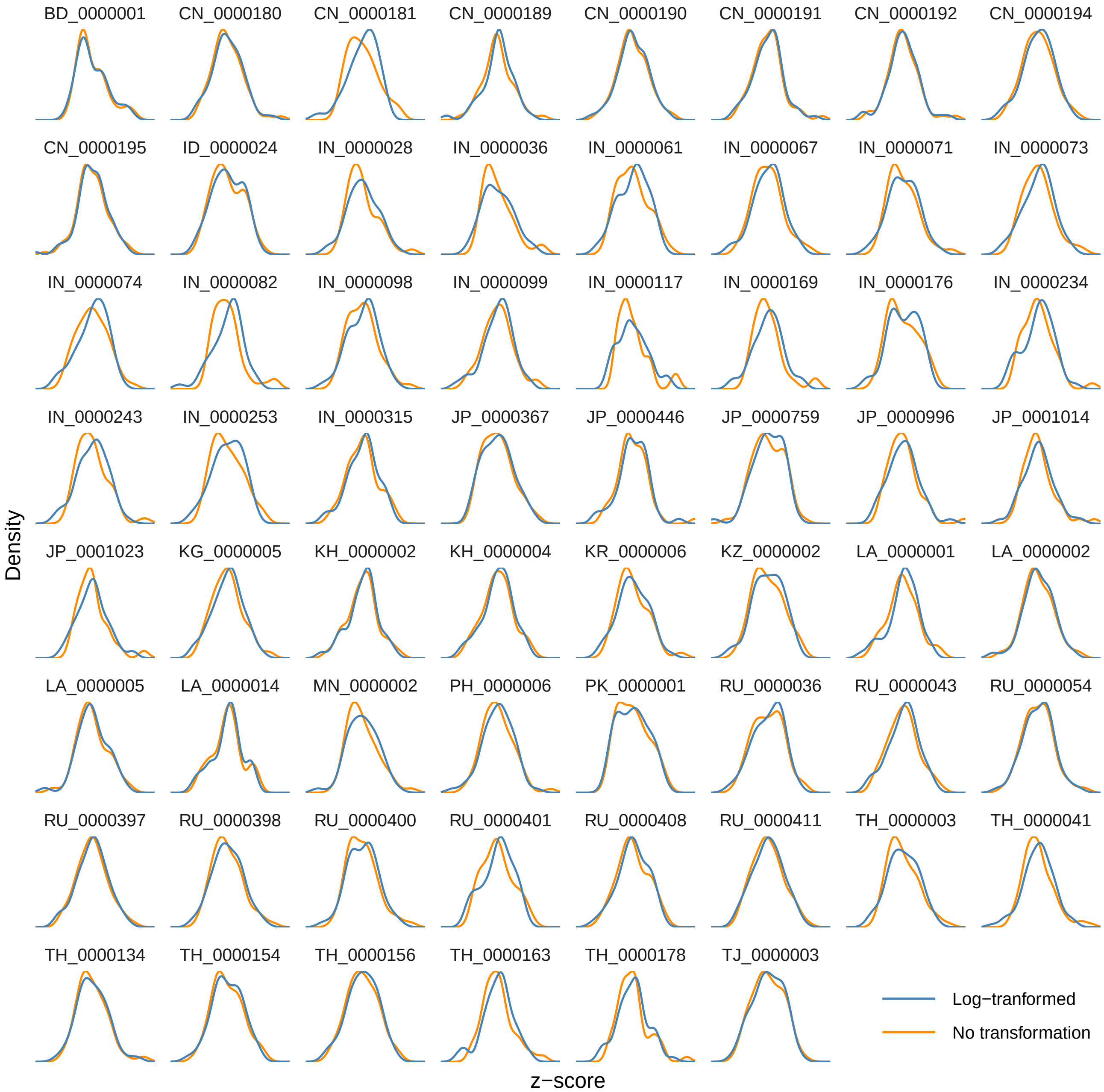

Figure S3. Densities of the transformed and untransformed flow at each station. The densities are centralized and rescaled for comparison.

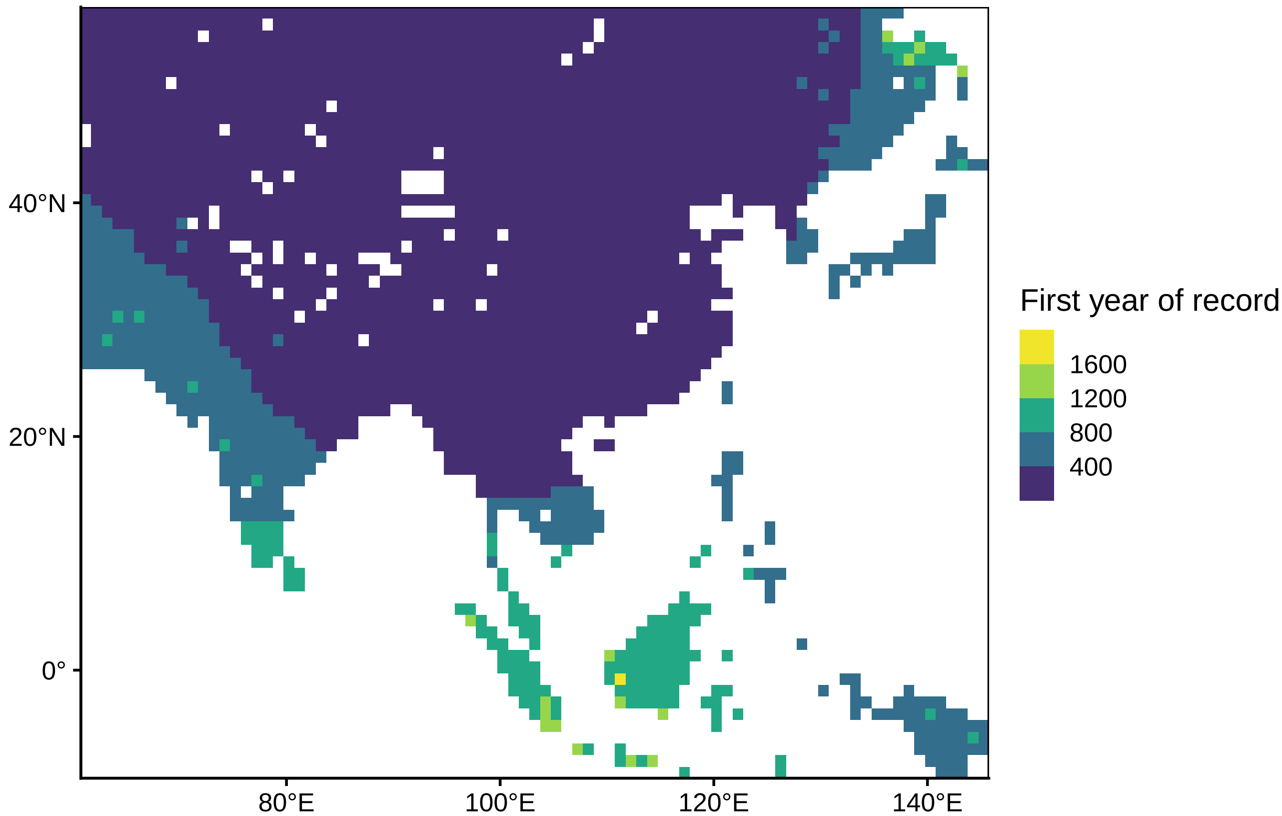

Figure S4. First year of record for each MADA grid point. 2716/2732 grid points start at or before 1200. The remaining grid points are not used.

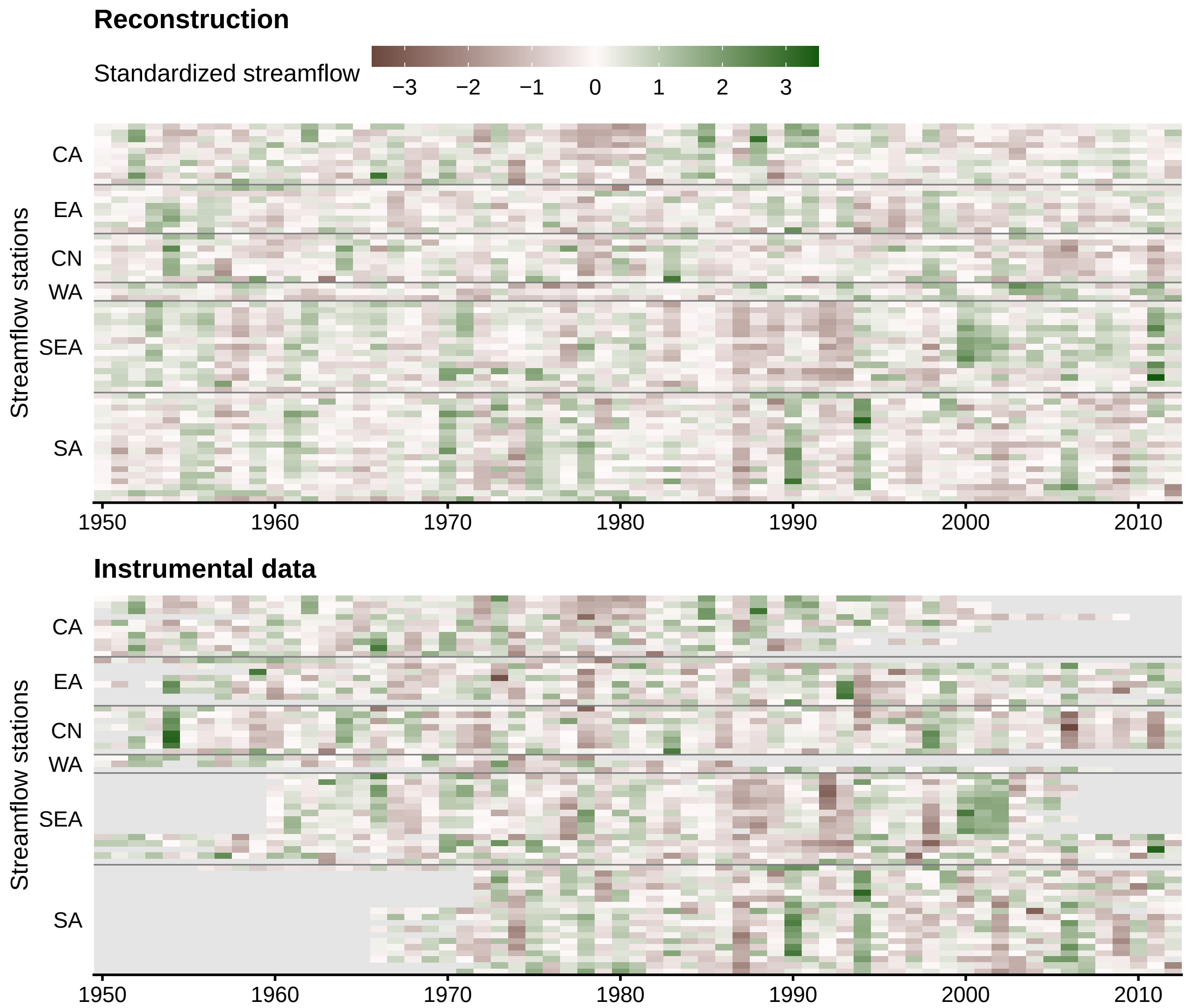

Figure S5. Comparing the reconstructed spatiotemporal variability of streamflow in the period 1950–2012 with instrumental streamflow data. Gray areas denote no data; color scale and annotations are the same as Figure 5 in the main text. The reconstruction captures well the spatial coherence and the extreme events in this period.

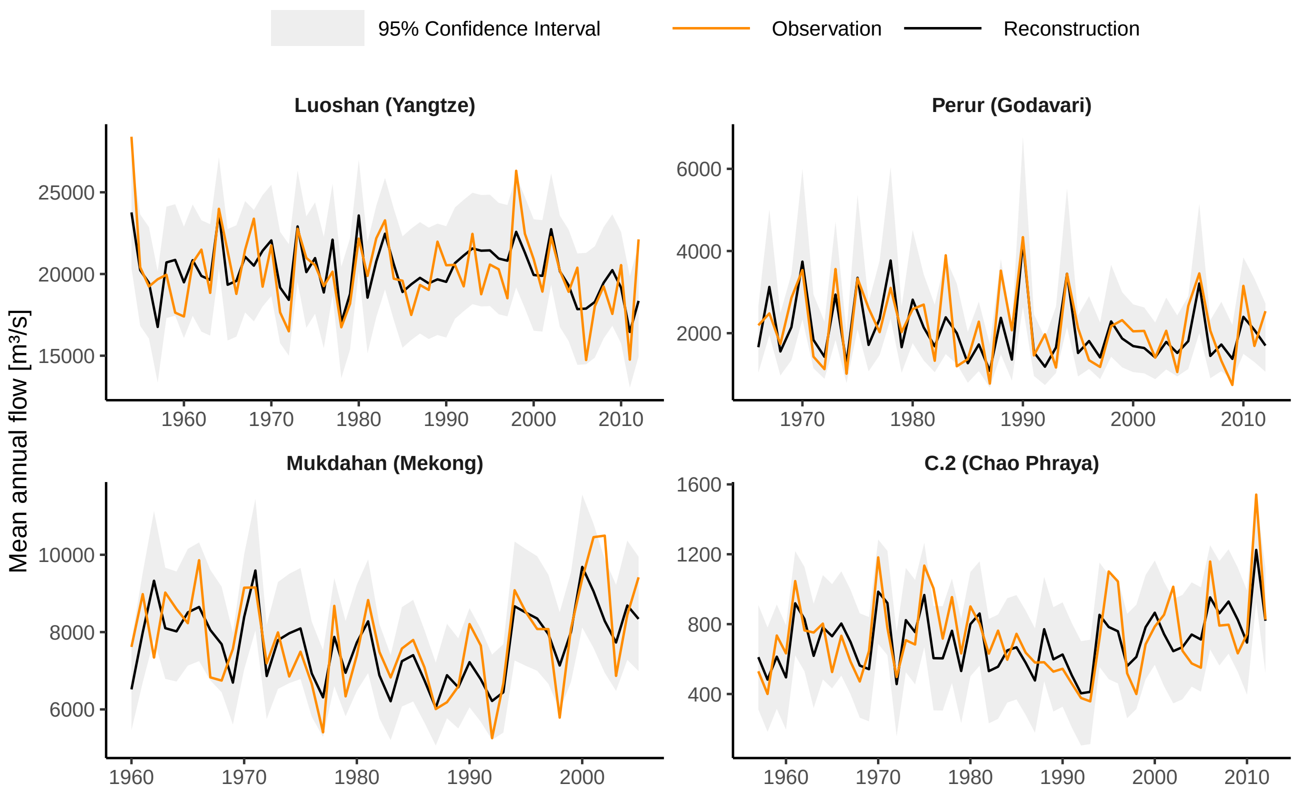

Figure S6. Comparing reconstructions and observations for the instrumental period at four representative stations (those used in Figures 3 and 6 of the main text).

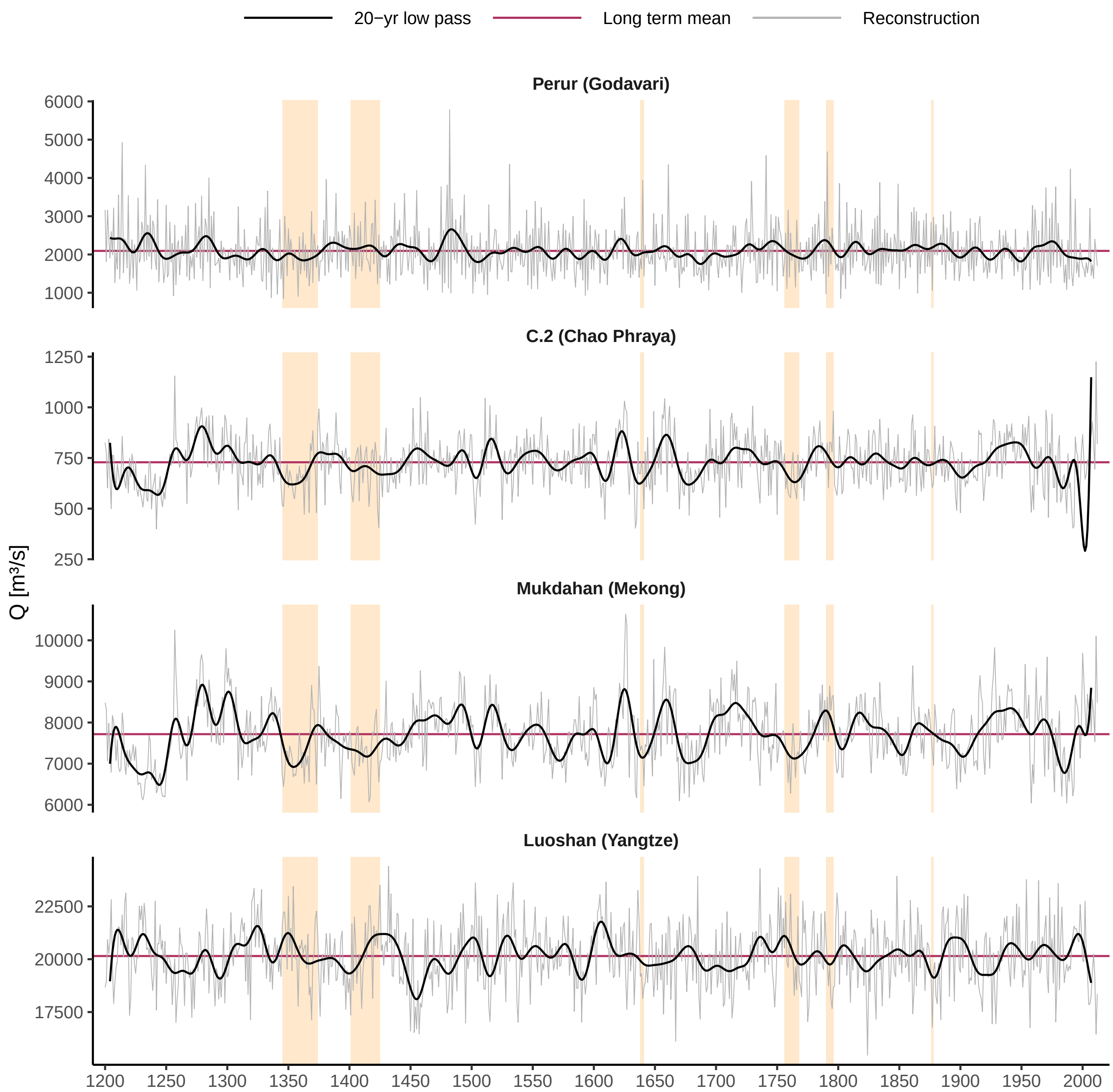

Figure S7. Full reconstruction time series for the same four stations shown in Figure S6. Vertical shaded areas show the megadroughts of Figure 5 in the main text (from left to right: Angkor Drought I, Angkor Drought II, Ming Dynasty Drought, Strange Parallels Drought, East India Drought, and Victorian Great Drought).

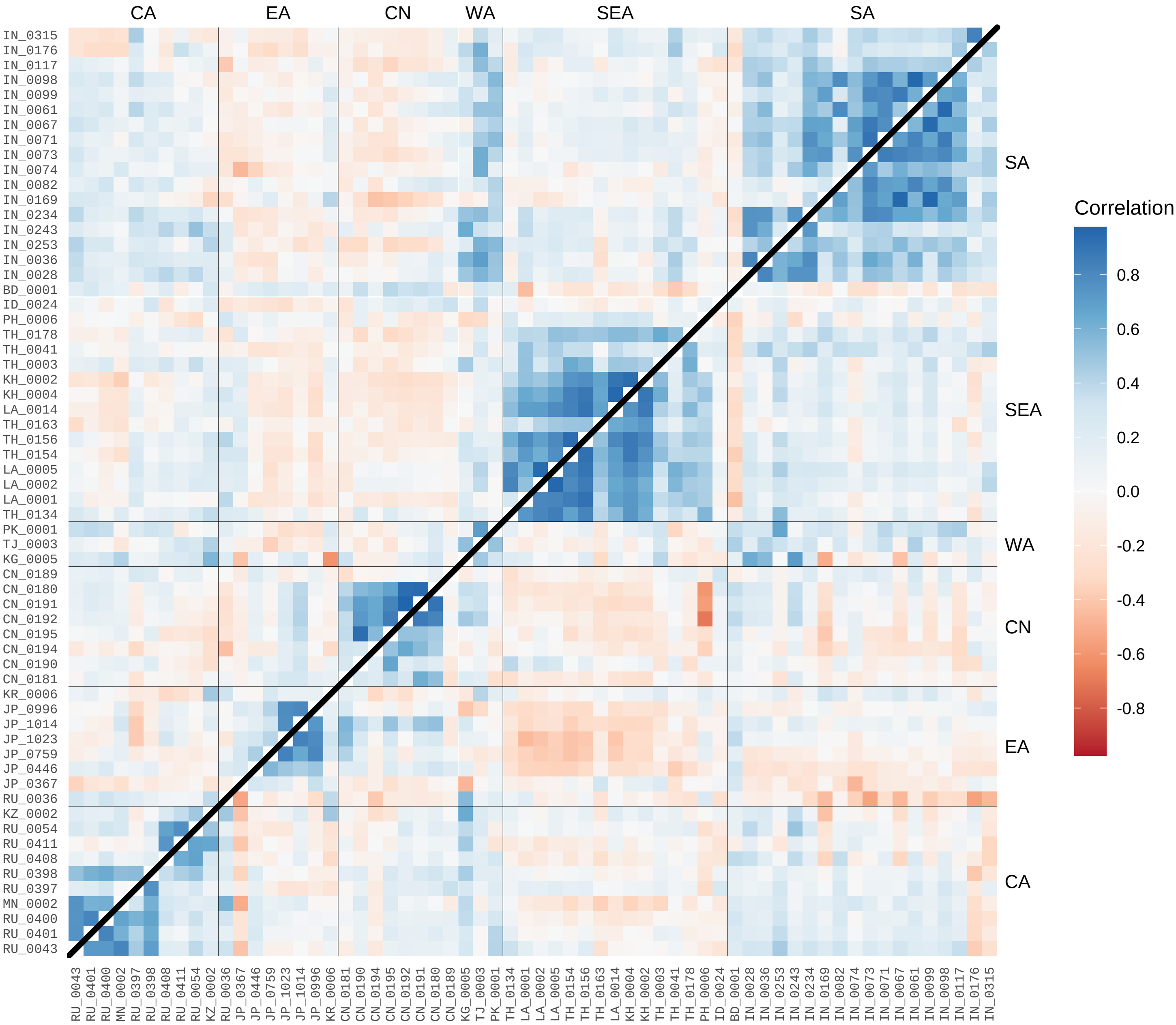

Figure S8. Composite correlation matrix of streamflow. The top half shows the correlations in the instrumental data; the bottom half the reconstruction. Stations are grouped by their region (according to Figure 1 of the main text) and follows the same order as in Figure 5 of the main text. This composite correlation matrix is close to symmetry about its diagonal; in other words, the reconstruction captures the correlation structure of the streamflow network.

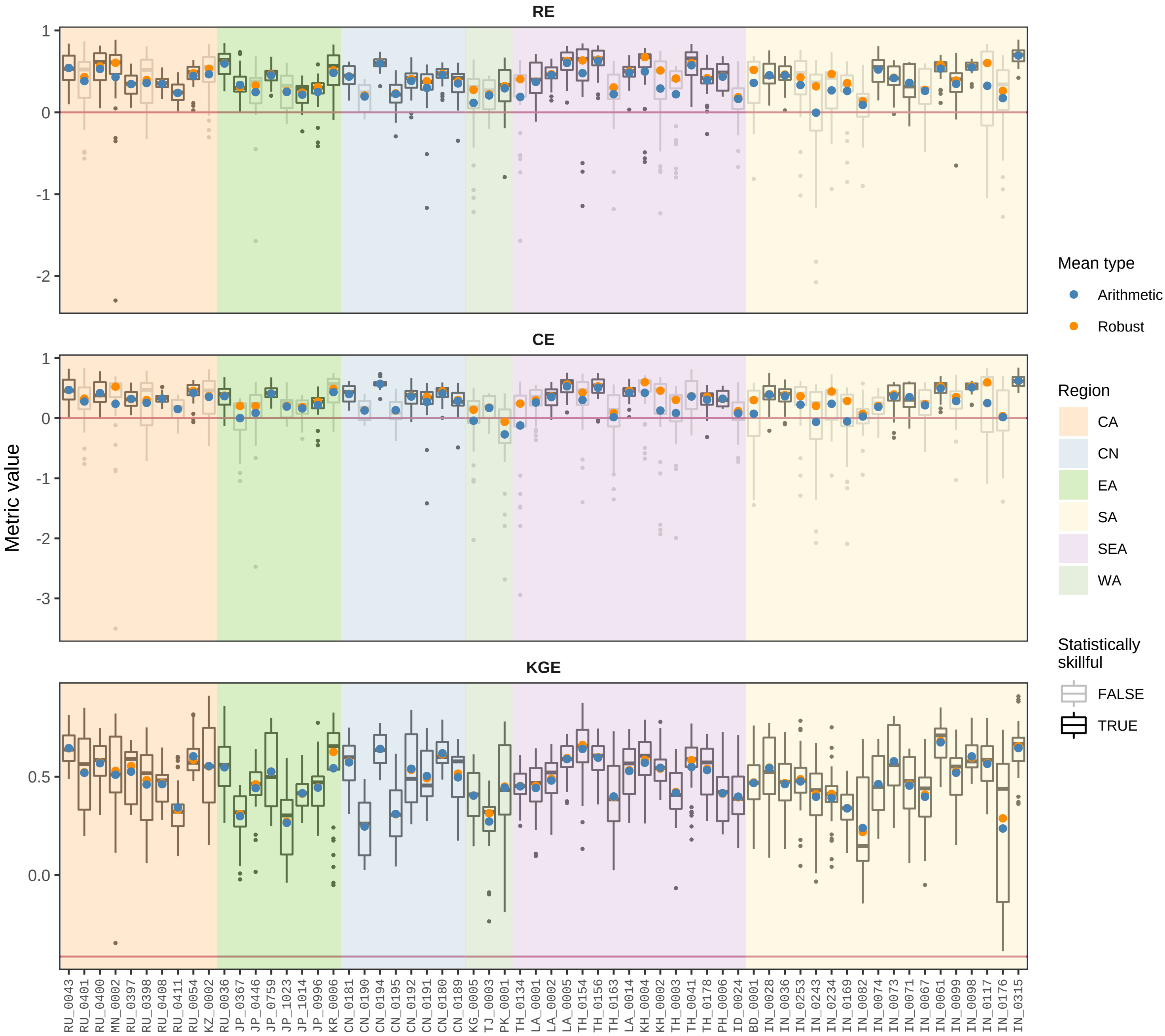

Figure S9. Distribution of performance scores. As explained in Section 3.2.3 of the main text, the reconstruction is considered statistically skillful at level α with respect to a metric if the probability of that metric being worse than the benchmark is less than α. Here we used $\alpha = 0.1$. The benchmark, shown as maroon horizontal line, equals zero for RE and CE, and equals $1 - \sqrt{2}$ for KGE. "Robust mean" refers to the Tukey's biweight robust mean (Mosteller & Tukey, 1977; Cook & Kairiukstis, 1990).

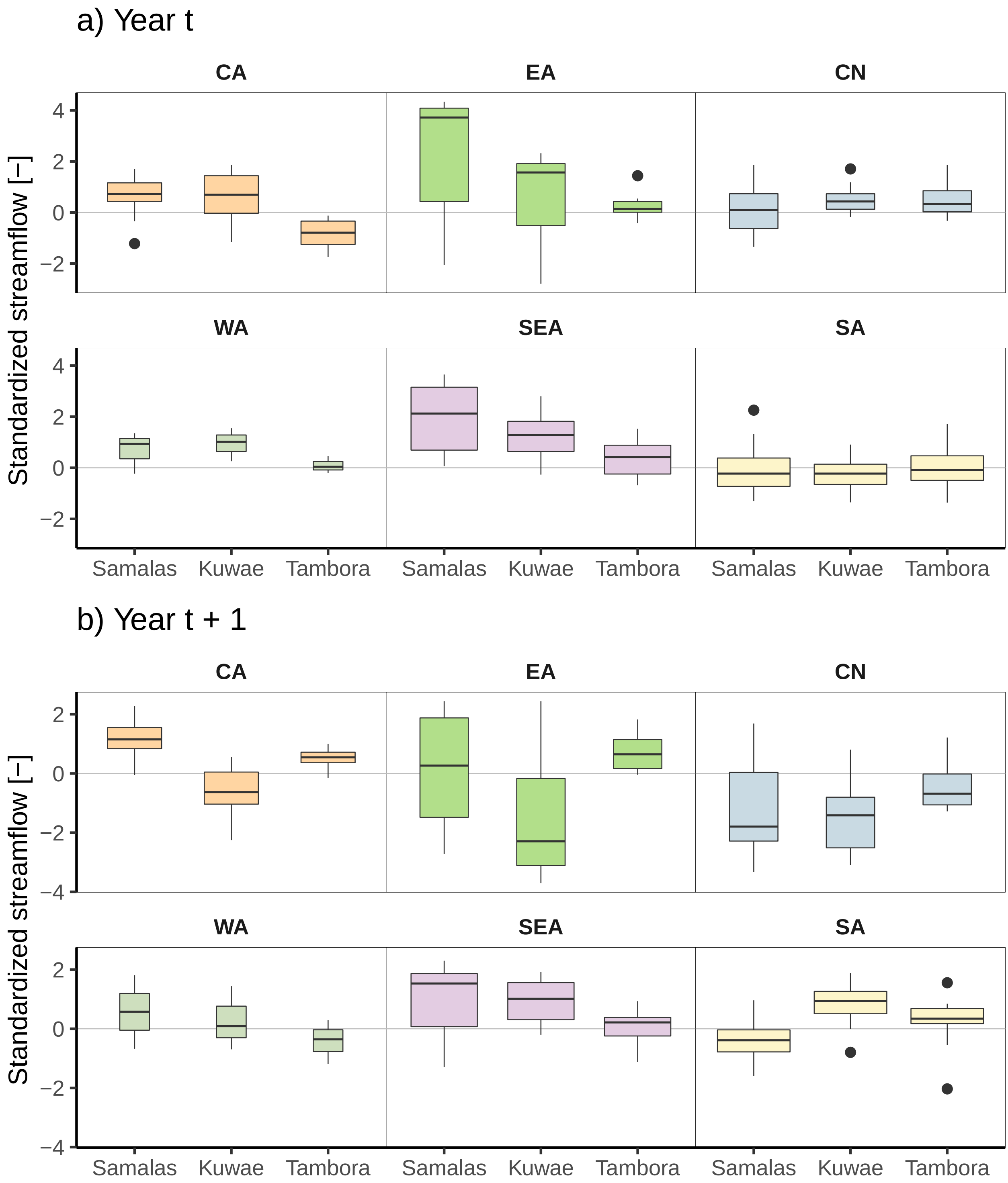

Figure S10. Distribution of standardized streamflow index in three volcanic eruptions. The widths of the box plots are proportional to their sample sizes.

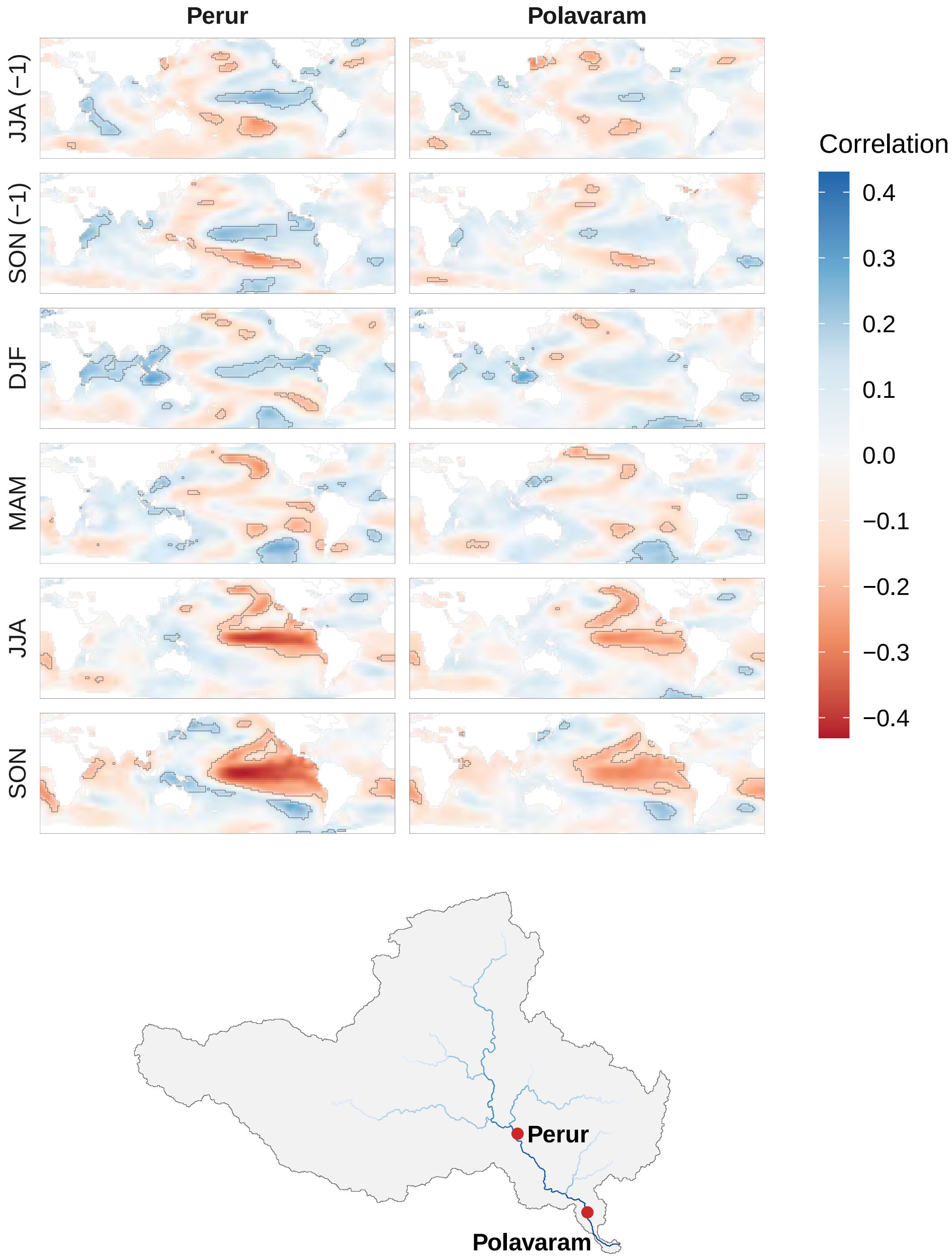

Figure S11. Same as Figure 6 in the main text, but for the Godavari River.

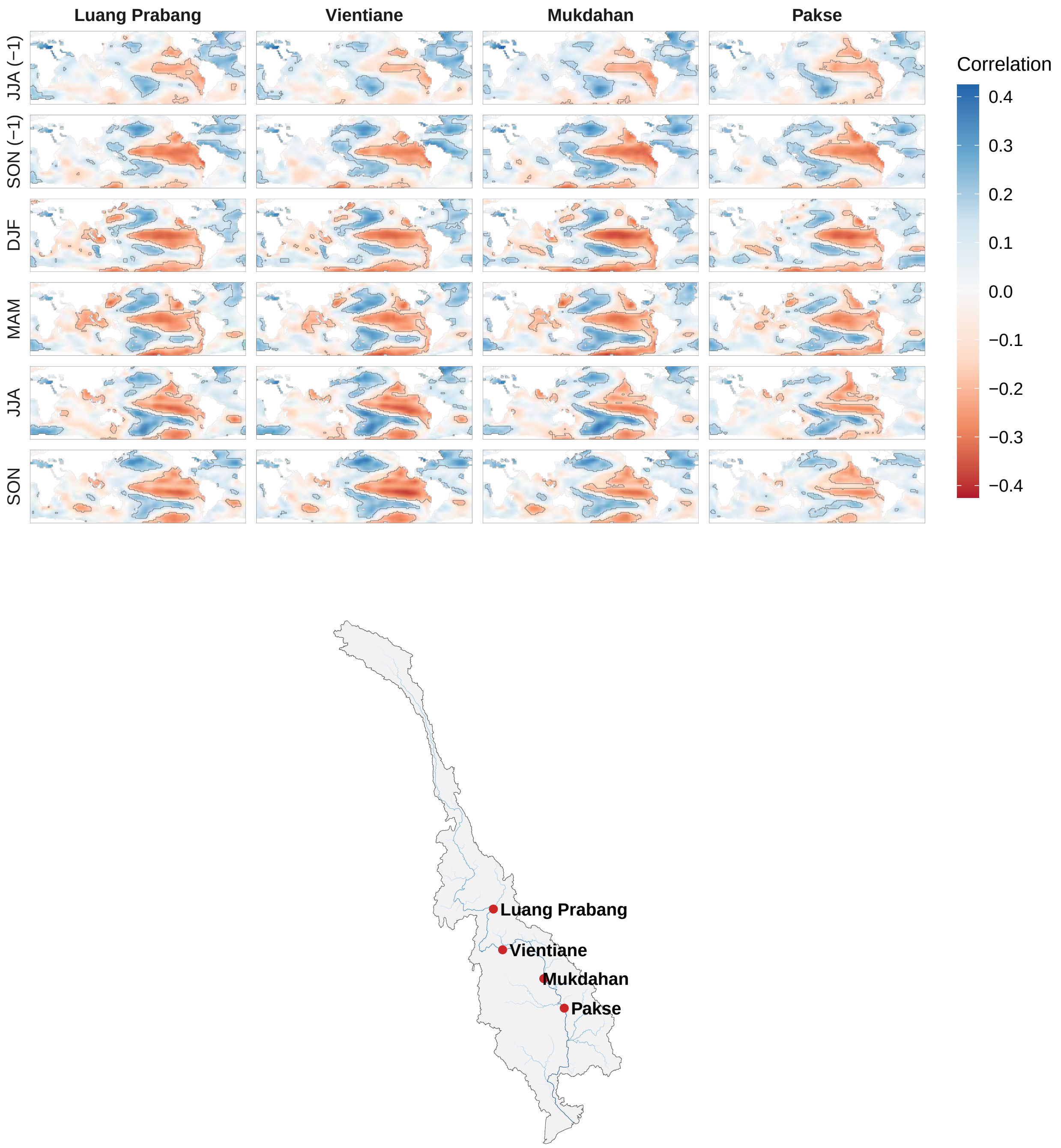

Figure S12. Same as Figure 6 in the main text, but for the Mekong River.

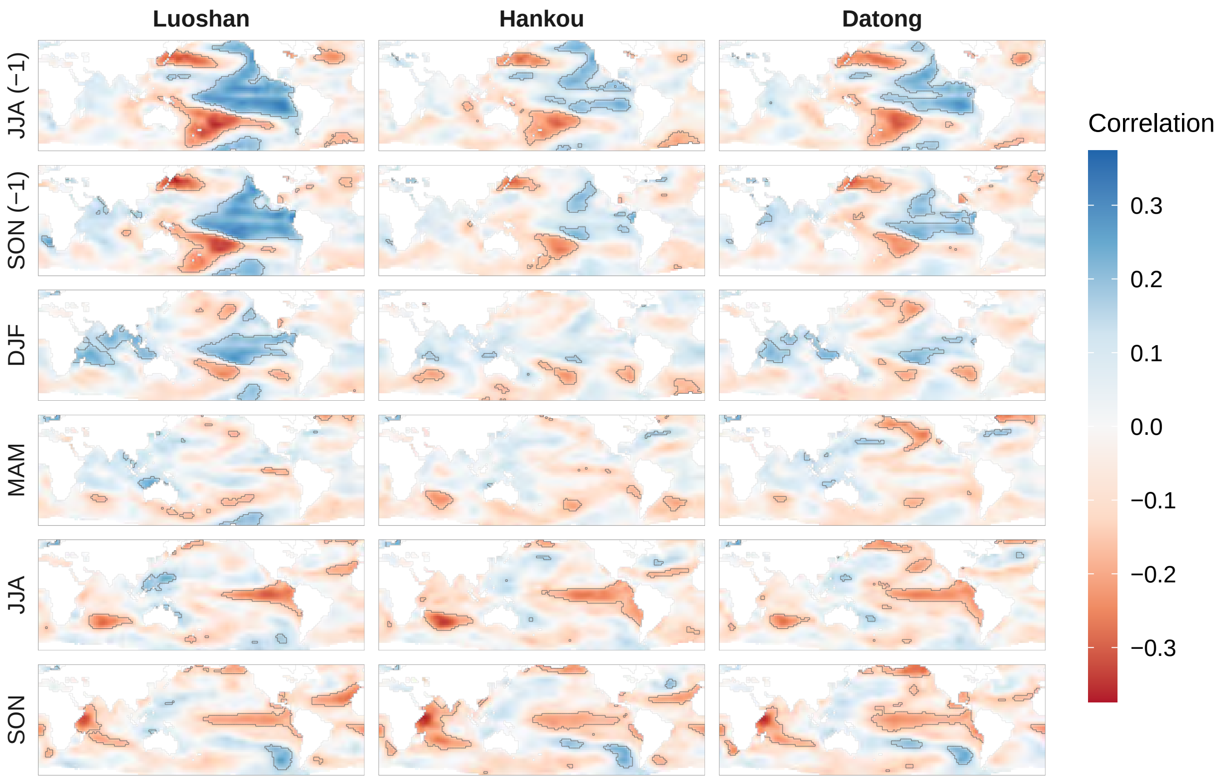

Figure S13. Same as Figure 6 in the main text, but for the Yangtze River.

Table S1. List of Monsoon Asia streamflow reconstruction papers

Reference	Proxy	River	Country
Davi et al. (2006)	Tree ring	Selenge	Mongolia
Yuan et al. (2007)	Tree ring	Manasi	China
X. Gou et al. (2007)	Tree ring	Yellow	China
Liu et al. (2010)	Tree ring	Heihe	China
X. H. Gou et al. (2010)	Tree ring	Yellow	China
D'Arrigo et al. (2011)	Tree ring	Citarum	Indonesia
Yang et al. (2012)	Tree ring	Heihe	China
Cook et al. (2013)	Tree ring	Indus	Pakistan
Davi et al. (2013)	Tree ring	Kherlen	Mongolia
Pederson et al. (2013)	Tree ring	Yeruu	Mongolia
Xu et al. (2015)	Stalagmite $\delta^{18}O$	Jialingjiang	China
Chen, Yuan, Davi, and Zhang (2016)	Tree ring	Irtysh	China
Chen and Yuan (2016)	Tree ring	Guxiang	China
Chen, Yuan, Zhang, et al. (2016)	Tree ring	Shiyang	China
D. Zhang et al. (2016)	Tree ring	Aksu	China
R. Zhang et al. (2016)	Tree ring	Tuoshigan	China
Chen et al. (2017)	Tree ring	Kurshab	Kyrgyzstan
Panyushkina et al. (2018)	Tree ring	Ili	Kazakhstan
T. Zhang et al. (2018)	Tree ring	Haba	China
Rao et al. (2018)	Tree ring	Indus	Pakistan
Nguyen and Galelli (2018)	MADA[a]	Ping	Thailand
Li et al. (2018)	Tree ring	Yangtze	China
Chen, Shang, Panyushkina, Meko, Yu, et al. (2019)	Tree ring	Lhasa	China
Chen, Shang, Panyushkina, Meko, Li, et al. (2019)	Tree ring	Salween	China
Yang et al. (2019)	Tree ring	Lancang	China
Li et al. (2019)	Tree ring	Yellow	China
Xu et al. (2019)	Tree ring $\delta^{18}O$	Chao Phraya	Thailand

[a] Monsoon Asia Drought Atlas (Cook et al., 2010)

Table S2. Metadata of the streamflow stations used. This large table is uploaded separately as "table_S2.csv"