SI Appendix for “River-discharge effects on United States Atlantic and Gulf coast sea-level changes”

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Additional details regarding data. We consider 24 tide-gauge relative sea-level records along the United States Atlantic and Gulf coasts (Fig. 1a; Table S1). These monthly data were extracted from the website* for the PSMSL RLR database (1) on 5 March 2018. Each time series has between 49–108 gauge-years of values. Annual water-year averages were computed from these monthly mean sea-level values.

We also use discharge data from 250 different stations along 26 rivers (Fig. 1a; Table S2). These annual water-year records were downloaded from the USGS Water Data for the Nation website† on 15 March 2018. The 250 stations constitute all the stations up and down these 26 rivers for which annual discharge data were available. The number of stations per river ranges from 2 (Edisto River) to 37 (Mississippi River). Descriptions of all river discharge stations used are included in Table S3.

Production of discharge time series for individual rivers. The USGS station records paint an incomplete picture of variable river discharge in space and time. For a given river, data from different stations can have different lengths, starting and stopping intermittently at different points, with many records featuring gaps (e.g., Fig. S5a). Moreover, time-mean discharge values and magnitudes of temporal variations can vary dramatically from one station to another along a given river (e.g., Fig. S5a). These realities make it challenging to derive a consistent, complete discharge record for a river over the 1910–2017 study period.

However, taking the logarithm of the discharge records along a river, we see that variations in

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* http://www.psmsl.org/data/

† https://waterdata.usgs.gov/nwis

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log-transformed river discharge are strongly correlated and that magnitudes of log-transformed discharge fluctuations are comparable from one station to another (e.g., Fig. S5b). Such results are expected from simple physical considerations. Consider a rectangular river of width w, depth d, and length l. This river is situated within a rectangular watershed, which has the same length l but broader width $W > w$. Suppose also the river is "closed" at $x = 0$ and "open" at $x = l$, emptying into a coastal ocean, where x is the coordinate along the river's length, and that precipitation falls over the watershed at a spatially uniform but temporally variable volumetric rate per area $q(t)$ and that there is no evaporation. To conserve volume, the river velocity $v(x, t)$ at $x = \ell$ (where $\ell \in \{0, l\}$) must be $v(\ell, t) = q(t)W\ell/wd$. The logarithm of this expression can be written as a sum of two terms: $\log[v(x, t)] = \log(W\ell/wd) + \log[q(t)]$. Because $W\ell/wd$ is a constant for a given river station, this implies that temporal variations in log-transformed river flow, while offset by constant values, will be identical from one river station to the next, independent of their respective locations along the river.

We use this line of reasoning to produce time series of river discharge as follows. First, for a given river, we compute the logarithm of all station discharge time series (e.g., Fig. S5b). Second, we remove the time-mean values from each of the log-transformed time series (Fig. S5c). Third, we compute the ensemble average (across stations) of these anomalous log-transformed time series, ignoring any gaps (Fig. S5c). Fourth, we add back the respective mean values to the individual log-transformed time series that were removed earlier (Fig. S5d), and then exponentiate the resulting time series (Fig. S5e). Fifth, in keeping with the simplifying assumption that discharge increases monotonically from the head to the mouth of the river, we choose the resulting time series with the largest time-mean value to be the river's discharge time series to be compared with sea-level records.

We find that, for most rivers, this algorithm is capable of filling most data gaps and returning nearly complete river-discharge time series that are extremely correlated (typical correlation coefficients ~ 0.99; Fig. S5f) with the original but gappy and incomplete data. However, there are some generally smaller rivers (e.g., Cape Fear River, Neuse River) for which data are too sparse, and this algorithm

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could not address all gaps for the lack of data. We believe this simple algorithm is appropriate and sufficient in the present study focusing on establishing basic relationships between river discharge and sea level. However, future studies should consider using more sophisticated techniques for jointly filling gaps in the river-discharge and sea-level data (2).

Construction of regional time series. Following previous studies (3–5), to form regional sea-level time series, we removed the linear trend given the available data from each tide-gauge record. Then, for each of the four study regions, we averaged together the residual sea-level time series within any given region, ignoring any data gaps. The resulting regional time series are highly correlated with each of the original data records (Fig. S6).

Similarly, to compute regional river-discharge time series, we first removed linear trends (including time-mean values) from the data records. Then, for each region, we summed up the individual compiled river-discharge records (generated as described in the previous section) over that record, again ignoring missing values. Finally, we added back the sum of time-mean river-discharge values for that region (Fig. S7).

Adjustment for climate. A principal task of sea-level science is to causally attribute historical observations of past sea-level changes. As explained in the introduction, changes in sea level can arise from myriad climate-system processes (3, 4, 6–18). Given the coupled nature of the climate system, causal attribution of sea level can be challenging, partly because there can be covariation between underlying processes driving changes in sea level, for example, winds and pressure (19). Partly for this reason, studies of dynamic sea-level changes (i.e., sea-level changes coupled to changes in ocean circulation) often adjust tide-gauge records prior to analysis. One such common correction is the so-called "inverted barometer" correction, whereby the influence of barometric pressure (which effects no changes in ocean circulation on time scales longer than a few days) is removed from sea-level records (14).

We attempt to identify the causal influence of river discharge on sea level. Since variable river discharge can be correlated with other climate processes (20), we desire to remove (as much as possible) the confounding effects of other processes from consideration. A challenge here relates to our study period, which goes back to 1910: relevant local observations (e.g., of longshore winds or air pressure) needed for adjusting tide gauges and river records become sparser (or do not exist) earlier in time. Rather than attempt to adjust the data using incomplete local records, our approach is to remove from the tide-gauge and river-discharge time series any signals related to major modes of climate variation, which we believe are better constrained and capture some of the relevant large-scale behavior (in wind, pressure, etc.). Indeed, past studies find that adjusting tide-gauge records for large-scale modes of climate variability using linear regression can reduce the variance in the sea-level data (10, 11, 21, 22). Here we consider four large-scale modes of climate variability that have previously been shown to be significantly correlated with annual sea-level records at various locations along the United States Atlantic and Gulf coasts: North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and the El Niño-Southern Oscillation (ENSO), in the form of the Niño 3.4 index. For all climate modes, we downloaded monthly time series from the website[‡] for the Working Group on Surface Pressure (WGSP) hosted by the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) Physical Sciences Division (PSD) on 17 March 2018 and computed annual water-year averages over the 1910–2017 period.

Thus, we do not perform the traditional inverted-barometer correction. Rather, to adjust the data, for each local and regional river-discharge and sea-level time series, we computed the correlation coefficient between the river-discharge or sea-level record and the given climate mode and the climate mode's Hilbert transform (to consider out-of-phase relationships). For each data time series, we used ordinary or multiple linear regression to remove estimated contributions due to all climate modes (and/or their Hilbert transforms) for which the correlation coefficient between the data and climate mode was statistically significant at the $p < 0.05$ level (one-sided test). Table S4 details which climate modes and their Hilbert transforms are significantly correlated (or not) with each regional river-discharge and sea-level time series.

For context, we find that, for regional river discharge, adjusting for climate modes reduces the variance in the Gulf of Maine regional record by 0% (no significantly correlated climate modes),

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[‡] https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/

Mid-Atlantic Bight by 0% (no significantly correlated climate modes), South Atlantic Bight by 10%, and Gulf of Mexico by 3%. Significant correlation found here between the AMO and river discharge over the Gulf of Mexico agrees with ref. (20), who determine that Mississippi River outflows can vary by $\sim \pm 10\%$ and that flows into Lake Okeechobee (Florida) can vary by $\sim \pm 40\%$ between warm and cool phases of the AMO. For regional sea level, removing climate-mode contributions reduces the variance in the Gulf of Maine record by 34%, Mid-Atlantic Bight by 13%, South Atlantic Bight by 12%, and Gulf of Mexico by 15%. The comparatively larger variance reduction in the Gulf of Maine sea-level time series is mainly due to the influence of the NAO. This finding is consistent with studies that show an important role for local wind and pressure effects (which are partly tied to the NAO) on interannual coastal sea-level changes in this region (10, 14, 15), supporting the basic validity of our approach.

The adjustment for climate modes does not radically alter the time series under consideration. Removal of climate modes does not influence the statistical significance of the relationship between river runoff and sea level in any region. However, this adjustment reduces the best estimate of the regression coefficient between river runoff and sea level by 8–43% depending on region. In any case, we grant that, while designed to reduce the risk of conflating the influence of river discharge on sea level with that of other drivers (e.g., wind, pressure, etc.), subtracting signals due to climate modes also risks removing some of the physics of interest to this study. Targeted future modeling studies could be more helpful and informative in this regard.

Estimation of uncertainties on regression coefficients and p-values on correlation coefficients. To estimate uncertainties on regression coefficients and significances (p-values) on correlation coefficients, we use Monte Carlo simulation and phase scrambling (or randomization) as described in refs. (23) and (24). Specifically, given a pair of time series $x(t)$ and $y(t)$, we generate 1,000 pairs of random synthetic time series $\hat{x}(t)$ and $\hat{y}(t)$, such that the Fourier amplitudes of $\hat{x}(t)$ and $\hat{y}(t)$ are identical to those of $x(t)$ and $y(t)$; however, the phases have been "scrambled." The p-value on the correlation coefficient between $x(t)$ and $y(t)$ is computed as the fraction of $[\hat{x}(\mathrm{t}), \hat{y}(t)]$ pairs that have a larger correlation coefficient than between $x(t)$ and $y(t)$. Similarly, the uncertainty on the regression coefficient between $x(t)$ and $y(t)$ is the standard deviation of the 1,000 regression coefficients determined from comparing all random $[\hat{x}(\mathrm{t}), \hat{y}(t)]$ pairs.

Model assumptions. In the main text, we list key assumptions underlying the theory for sea level driven by river discharge. Here we give additional details, justifying some of these assumptions.

We assume that motions are in steady state. Let us reconsider the far-field offshore momentum equation, now modified to incorporate the time tendency of offshore velocity u,

$$\frac{\partial u}{\partial t} - fv = -g' \frac{\partial h}{\partial x}. \qquad [S1]$$

We perform a scaling analysis, inserting reasonable values for velocities, offshore distance, layer thickness, and reduced gravity from Table 2 in ref. (25). For low-frequency motions, with periods longer than one year, the time tendency is several orders of magnitude smaller than the Coriolis acceleration and pressure gradient. Thus, our assumption of steady state is reasonable given the long time scales of interest. However, while unimportant in the present context, deviations from steady state would be important for higher-frequency motions (e.g., time scales of days).

We also assume that ocean-mass changes due to river discharge contribute negligibly to coastal sea-level changes. In principle, changes in sea level represent changes in water volume, which can arise from changes in ocean mass (bottom pressure) or density (steric height). Here we represent coastal sea-level changes driven by river discharge wholly in terms of density changes, ignoring the effects of mass. However, since, the river discharge itself constitutes a mass source, it is not immediately obvious that mass contributions to sea-level changes at the coast can be ignored, and this point warrants further discussion.

As freshwater from rivers debouches into the coastal ocean, mass is displaced and redistributed. Generally speaking, mass redistribution in the ocean is strongly related to the ocean's barotropic (depth-independent) adjustment to surface forcing (26). Basic linear theory anticipates that a barotropic ocean equilibrates quasi-instantaneously to surface freshwater forcing (27), such that the ocean-mass field responds isostatically (i.e., supporting minimal horizontal pressure gradients), resulting in horizontally uniform redistribution of water mass over the global ocean surface. In such a case, local sea-level changes related to ocean-mass redistribution and forced by river discharge are expected to be negligible on the time scales of interest. Global barotropic ocean model simulations largely corroborate this theoretical notion for open coastlines, showing that the local ocean-mass response to variable surface freshwater forcing is relatively small ($\sim$ 1 mm root mean square variability on seasonal to daily time scales; see Fig. 5 in ref. (27)). For these reasons, we believe it is reasonable to assume that the influence of mass redistribution on coastal sea level is unimportant here.

Additional details regarding derivation. Here we detail the mathematical steps relating Equations [1–3] to Equation [4]. First, we divide Equation [2] by S_0 to solve for Q_E. We substitute this expression for Q_E on the right hand side of Equation [1]. After collecting terms and canceling common factors, one derives an expression relating Q_T and Q_F,

$$Q_T = \frac{S_0}{\delta S} Q_F. \qquad [S2]$$

This is a form of Knudsen's Hydrographical theorem (28). Now, by definition we have that,

$$Q_T = -\int_{x=0}^{x=\mathcal{W}} (vh)\, dx, \qquad [S3]$$

where $\mathcal{W}$ is the (unknown) width of the far-field alongshore flow at which point the buoyant layer thickness goes to zero. Combining Equations [$S3$] and [$S2$] gives,

$$\frac{S_0}{\delta S} Q_F = -\int_{x=0}^{x=\mathcal{W}} (vh)\, dx. \qquad [S4]$$

Multiplying Equation [3] by h, dividing by $-f$, and using the product rule gives,

$$vh = \frac{g'}{2f} \frac{\partial}{\partial x} h^2. \qquad [S5]$$

Substituting the right hand side of Equation $[S4]$ for vh within the integral on the left hand side of Equation $[S3]$ and evaluating the integral (recalling that h goes to zero at $x = \mathcal{W}$) gives,

$$\frac{g'}{2f} h_0^2 = \frac{S_0}{\delta S} Q_F. \qquad [S6]$$

Solving for h_0 in Equation $[S5]$ thus leads to the desired result.

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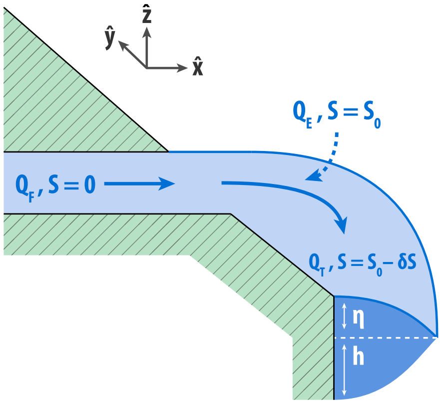

Fig. S1. Illustration of the key quantities used to construct the theoretical relationship between river discharge and sea level, showing river flow entering into the coastal ocean and flowing into an alongshore current in the Northern Hemisphere. Different volumetric flows (Q_F, Q_E, and Q_T) and salinities (S_0, δS) are shown, along with the layer-thickness (h) and sea-level (η) anomalies of interest. Arrows indicate the sense of the flow. For more detailed schematics, see Figs. 1, 2, and 4 in ref. (29).

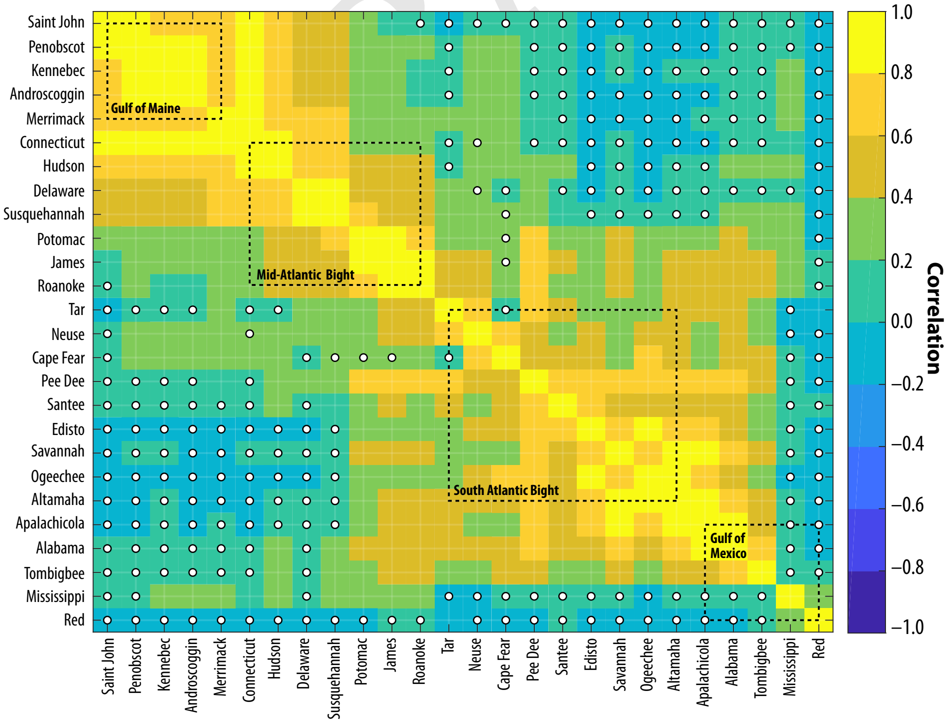

Fig. S2. Shading shows correlation coefficient between all possible pairs of river-discharge time series. All time series have been adjusted for large-scale climate modes as with the regional time series. White dots indicate values not statistically significant at the $p < 0.05$ level.

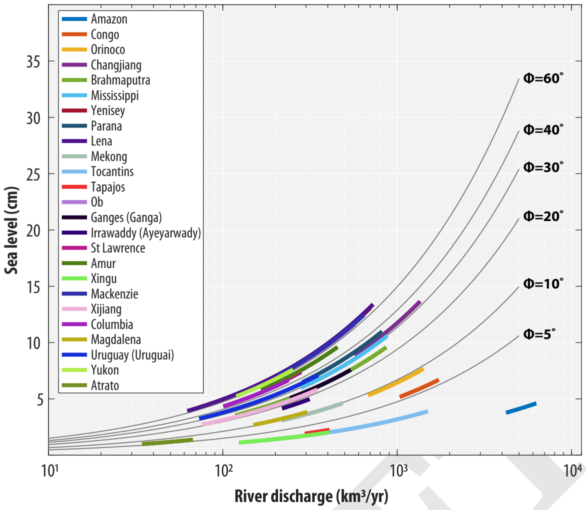

Fig. S3. Sea level driven by river discharge based on the theory developed here. Note the semilogarithmic horizontal axis. Black curves show sea level predicted by Equation [5] as a function of river discharge for a variety of latitude (Φ) values. Various colored sections indicate predicted range of sea-level for the 25 largest rivers in the world (by annual discharge), given the latitudes of and observations of annual discharge from those rivers (from the database of ref. (30)). For example, the Mackenzie River (dark blue curve; latitude 68.75°N) has a mean discharge observed over 1943–2010 of 287 km^3 yr^{-1} with a minimum annual-mean value of 206 km^3 yr^{-1} observed in 1995 and a maximum annual mean of 645 km^3 yr^{-1} observed in 1949 (30). Based on Equation [5], these discharge values translate to a mean downstream sea-increase of ~ 10 cm, with sea-level values ranging from a minimum of ~ 7 cm for lowest river discharge to a maximum of ~ 12 cm for highest river discharge.

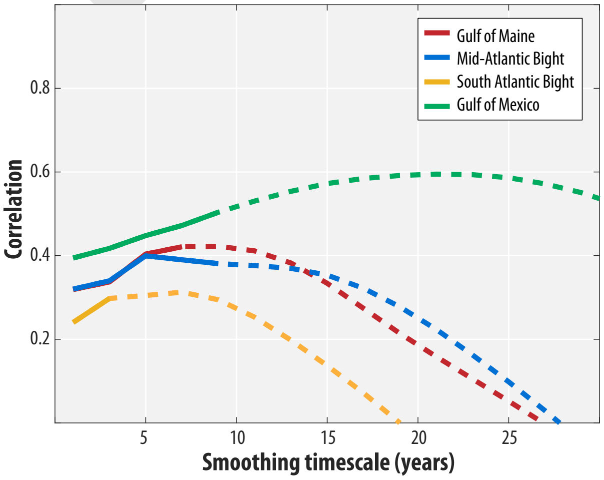

Fig. S4. Colored curves indicate the correlation coefficient between regional river-discharge and sea-level time series for the four different study regions as a function of the window size ("smoothing timescale") of a Hann filter applied to the data. Thick solid curves indicate correlation coefficients significant at the $p < 0.05$ level whereas thin dashed curves indicate values that are statistically insignificant.

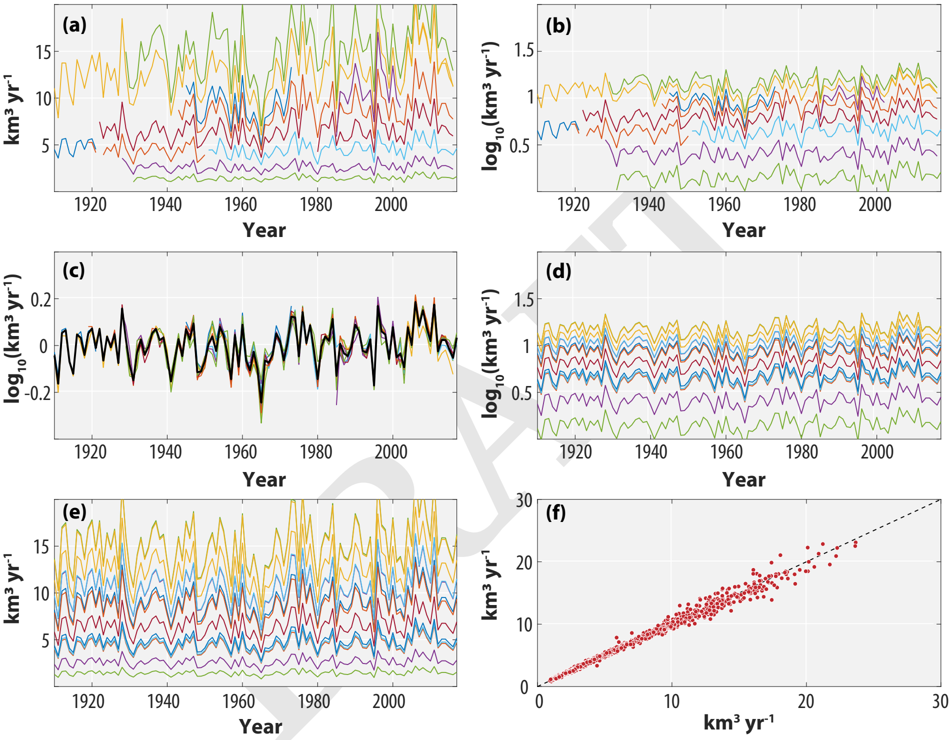

Fig. S5. Demonstration of the compilation of river-discharge time series for the example case of the Connecticut River. **a.** Different colors show raw discharge data series from 15 different stations along the river. **b.** Colored curves represent the logarithm (base 10) of the time series in a. **c.** Colored curves are identical to those in b but with the time-mean values removed. The black curve is the average across all colored curves (ignoring missing data). **d.** Colored curves represent respectively the black ensemble-averaged time series from c with the various individual time-mean values from the different river stations (formerly removed going from b to c) added back. **e.** Exponentiation of the time series in d. The time series with the largest mean value is taken as the time series to be used in comparison to sea-level data (stations indicated in Table S2). **f.** Orange dots are a scatter plot comparing the raw observed discharge data values (horizontal axis) plotted against the processed and recompiled discharge values (vertical axis) for all stations and time points with data. Blue dotted line is the 1:1 curve.

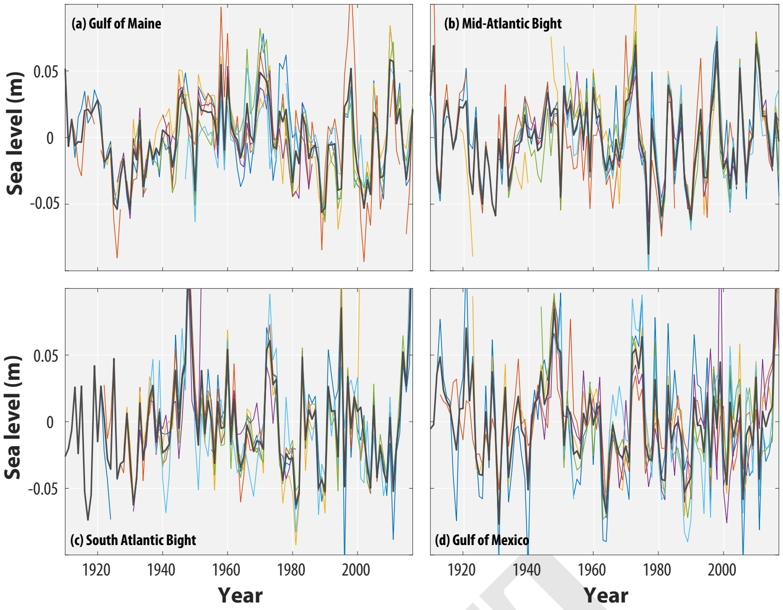

Fig. S6. Detrended annual water-mean average sea-level time series from individual tide-gauge stations (colors) and averaged over all tide gauges within a given region (black) for **a.** Gulf of Maine, **b.** Mid-Atlantic Bight, **c.** South Atlantic Bight, and **d.** Gulf of Mexico. See Fig. 1 for station locations. Note that these time series have not yet been adjusted for large-scale climate modes.

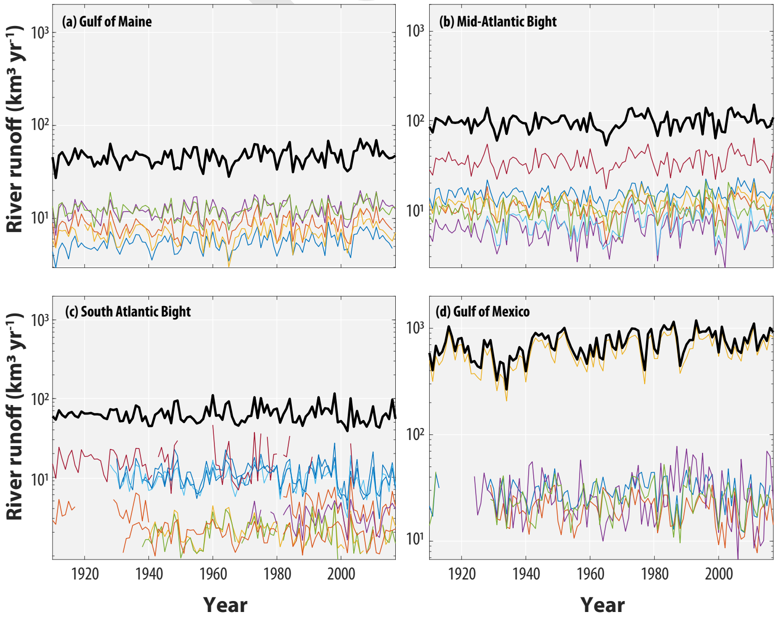

Fig. S7. Logarithm of detrended annual water-mean average river-discharge time series (but with time-mean values retained) from individual rivers (colors) and summed over all rivers within a given region (black) for **a.** Gulf of Maine, **b.** Mid-Atlantic Bight, **c.** South Atlantic Bight, and **d.** Gulf of Mexico. See Fig. 1 for station locations. Note that these time series have not yet been adjusted for large-scale climate modes.

No.	Region	Location, State	PSMSL ID	Longitude	Latitude	Duration (Completeness)
1	GME	Saint John, NB	195	66.1°W	45.3°N	1910–2017 (93%)
2	GME	Eastport, ME	332	67°W	44.9°N	1930–2017 (99%)
3	GME	Bar Harbor, ME	525	68.2°W	44.4°N	1947–2017 (99%)
4	GME	Portland, ME	183	70.2°W	43.7°N	1912–2017 (100%)
5	GME	Seavey Island, ME	288	70.7°W	43.1°N	1926–1986 (93%)
6	GME	Boston, MA	235	71.1°W	42.4°N	1921–2017 (100%)
7	MAB	Newport, RI	351	71.3°W	41.5°N	1931–2017 (100%)
8	MAB	New York, NY	12	74°W	40.7°N	1910–2017 (100%)
9	MAB	Atlantic City, NJ	180	74.4°W	39.4°N	1911–2017 (98%)
10	MAB	Sandy Hook, NJ	366	74°W	40.5°N	1933–2017 (100%)
11	MAB	Lewes, DE	224	75.1°W	38.8°N	1919–2017 (81%)
12	MAB	Kiptopeke Beach, VA	636	76°W	37.2°N	1951–2017 (100%)
13	SAB	Wilmington, NC	396	78°W	34.2°N	1935–2017 (100%)
14	SAB	Charleston, SC	234	79.9°W	32.8°N	1922–2017 (100%)
15	SAB	Fort Pulaski, GA	395	80.9°W	32°N	1935–2017 (100%)
16	SAB	Fernandina Beach, FL	112	81.5°W	30.7°N	1910–2017 (87%)
17	SAB	Mayport, FL	316	81.4°W	30.4°N	1928–2001 (100%)
18	SAB	Miami Beach, FL	363	80.1°W	25.8°N	1931–1981 (96%)
19	GMX	Key West, FL	188	81.8°W	24.6°N	1913–2017 (100%)
20	GMX	Cedar Key, FL	428	83°W	29.1°N	1939–2017 (100%)
21	GMX	Pensacola, FL	246	87.2°W	30.4°N	1923–2017 (100%)
22	GMX	Galveston, TX	161	94.8°W	29.3°N	1910–2017 (100%)
23	GMX	Rockport, TX	538	97°W	28°N	1948–2017 (89%)
24	GMX	Port Isabel, TX	497	97.2°W	26.1°N	1944–2017 (99%)

Table S1. Listing of all tide-gauge relative sea-level records used here, given with their respective region, PSMSL ID, longitude and latitude, as well as the duration over 1910–2017 covered by the data and the record completeness (i.e., percent of years during the duration for which data are available). The regional acronyms are: GME (Gulf of Maine), MAB (Mid-Atlantic Bight), SAB (South Atlantic Bight), and GMX (Gulf of Mexico).

No.	Region	River Name	Location, State	USGS ID	Longitude	Latitude
1	GME	Saint John	Van Buren, ME	01015000	67.9°W	47.2°N
2	GME	Penobscot	Eddington, ME	01036390	68.7°W	44.8°N
3	GME	Kennebec	Waterville, ME	01049205	69.6°W	44.5°N
4	GME	Androscoggin	Auburn, ME	01059000	70.2°W	44.1°N
5	GME	Merrimack	Lowell, MA	01100000	71.3°W	42.6°N
6	MAB	Connecticut	Thompsonville, CT	01184000	72.6°W	42°N
7	MAB	Hudson	Green Island, NY	01358000	73.7°W	42.8°N
8	MAB	Delaware	Trenton, NJ	01463500	74.8°W	40.2°N
9	MAB	Susquehanna	Conowingo, MD	01578310	76.2°W	39.7°N
10	MAB	Potomac	Washington, DC	01646502	77.1°W	38.9°N
11	MAB	James	Cartersville, VA	02035000	78.1°W	37.7°N
12	MAB	Roanoke	Clarksville, VA	02079000	78.6°W	36.6°N
13	SAB	Tar	Greenville, NC	02084000	77.4°W	35.6°N
14	SAB	Neuse	Fort Barnwell, NC	02091814	77.3°W	35.3°N
15	SAB	Cape Fear	Kelly, NC	02105769	78.3°W	34.4°N
16	SAB	Pee Dee	Bucksport, SC	02135200	79.2°W	33.7°N
17	SAB	Santee	Ferguson, SC	02170000	80.3°W	33.4°N
18	SAB	Edisto	Givhans, SC	02175000	80.4°W	33°N
19	SAB	Savannah	Cylo, GA	02198500	81.3°W	32.5°N
20	SAB	Ogeechee	Eden, GA	02202500	81.4°W	32.2°N
21	SAB	Altamaha	Doctortown, GA	02226000	81.8°W	31.7°N
22	GMX	Apalachicola	Sumatra, FL	02359170	85°W	29.9°N
23	GMX	Alabama	Claiborne, AL	02429500	87.5°W	31.5°N
24	GMX	Tombigbee	Coffeeville, AL	02469761	88.1°W	31.8°N
25	GMX	Mississippi	Vicksburg, MS	07289000	90.9°W	32.3°N
26	GMX	Red	Alexandria, LA	07355500	92.4°W	31.3°N

Table S2. Listing of all main river-discharge records used here, given along with their respective region, USGS ID, the location of the river gauge, as well as the location's longitude and latitude. Note that gaps in the discharge records have been filled where possible using methods described in the SI Appendix. The regional acronyms are: GME (Gulf of Maine), MAB (Mid-Atlantic Bight), SAB (South Atlantic Bight), and GMX (Gulf of Mexico).

River	USGS ID	USGS Site Name
Alabama River	02423000	ALABAMA RIVER AT SELMA AL
Alabama River	02427500	ALABAMA RIVER NEAR MILLERS FERRY AL
Alabama River	02420000	ALABAMA RIVER NEAR MONTGOMERY, AL.
Alabama River	02429500	ALABAMA RIVER AT CLAIBORNE AL
Alabama River	02428400	ALABAMA RIVER AT CLAIBORNE L&D NEAR MONROEVILLE
Altamaha River	02226000	ALTAMAHA RIVER AT DOCTORTOWN, GA
Altamaha River	02225000	ALTAMAHA RIVER NEAR BAXLEY, GA
Altamaha River	02224940	ALTAMAHA RIVER AT US 221, NR CHARLOTTEVILLE, GA
Androscoggin River	01053600	Androscoggin River below Bog Brook at Cambridge NH
Androscoggin River	01053500	Androscoggin River at Errol, NH
Androscoggin River	01059000	Androscoggin River near Auburn, Maine
Androscoggin River	01054000	Androscoggin River near Gorham, NH
Androscoggin River	01054500	Androscoggin River at Rumford, Maine
Apalachicola River	02358700	APALACHICOLA RIVER NR BLOUNTSTOWN,FLORIDA
Apalachicola River	02359170	APALACHICOLA RIVER NR SUMATRA,FLA.
Apalachicola River	02358754	APALACHICOLA R.AB CHIPOLA CONR WEWAHITCHKA,FLA
Apalachicola River	02358000	APALACHICOLA RIVER AT CHATTAHOOCHEE FLA
Apalachicola River	02358754	APALACHICOLA RIVER AT MILE 36.0
Cape Fear River	02105769	CAPE FEAR R AT LOCK #1 NR KELLY, NC
Cape Fear River	02105500	CAPE FEAR R AT WILM O HUSKE LOCK NR TARHEEL, NC
Cape Fear River	02104000	CAPE FEAR RIVER AT FAYETTEVILLE, NC
Cape Fear River	02102500	CAPE FEAR RIVER AT LILLINGTON, NC
Connecticut River	01156500	CONNECTICUT RIVER AT VERNON, VT
Connecticut River	01139500	CONNECTICUT RIVER AT SOUTH NEWBURY, VT
Connecticut River	01170500	CONNECTICUT RIVER AT MONTAGUE CITY, MA
Connecticut River	01131500	CONNECTICUT RIVER NEAR DALTON, NH
Connecticut River	01184000	CONNECTICUT RIVER AT THOMPSONVILLE, CT
Connecticut River	01138500	CONNECTICUT RIVER AT WELLS RIVER, VT
Connecticut River	01144500	CONNECTICUT RIVER AT WEST LEBANON, NH
Connecticut River	01140500	CONNECTICUT RIVER AT ORFORD, NH
Connecticut River	01154500	CONNECTICUT RIVER AT NORTH WALPOLE, NH
Connecticut River	01129200	CONNECTICUT R BELOW INDIAN STREAM NR PITTSBURG, NH
Connecticut River	01172010	CONNECTICUT R AT I-391 BRIDGE AT HOLYOKE, MA
Connecticut River	01172003	CONNECTICUT RIVER BELOW POWER DAM AT HOLYOKE,MA
Connecticut River	01129500	CONNECTICUT RIVER AT NORTH STRATFORD, NH
Connecticut River	01172000	CONNECTICUT RIVER AT HOLYOKE, MA
Connecticut River	01128500	CONNECTICUT R AT FIRST CONN LK NR PITTSBURG, NH
Delaware River	01427207	DELAWARE RIVER AT LORDVILLE NY
Delaware River	01427405	DELAWARE R NR CALLICOON NY
Delaware River	01434000	DELAWARE RIVER AT PORT JERVIS NY
Delaware River	01460440	Delaware and Raritan Canal at Port Mercer NJ
Delaware River	01446700	Delaware River at Easton, PA
Delaware River	01428500	DELAWARE R ABOVE LACKAWAXEN R NEAR BARRYVILLE NY
Delaware River	01446500	Delaware River at Belvidere NJ
Delaware River	01463500	Delaware River at Trenton NJ
Delaware River	01438500	Delaware River at Montague NJ
Delaware River	01427510	DELAWARE RIVER AT CALLICOON NY
Edisto River	02174000	EDISTO RIVER NEAR BRANCHVILLE, SC
Edisto River	02175000	EDISTO RIVER NR GIVHANS, SC
Hudson River	01314000	HUDSON R AT GOOLEY, NEAR INDIAN LAKE NY
Hudson River	01331095	HUDSON RIVER AT STILLWATER NY
Hudson River	01312000	HUDSON RIVER NEAR NEWCOMB NY
Hudson River	01335754	HUDSON RIVER ABOVE LOCK 1 NEAR WATERFORD NY
Hudson River	01327750	HUDSON RIVER AT FORT EDWARD NY
Hudson River	01326500	HUDSON RIVER AT SPIER FALLS NY
Hudson River	01315500	HUDSON RIVER AT NORTH CREEK NY
Hudson River	01318500	HUDSON RIVER AT HADLEY NY
Hudson River	01358000	HUDSON RIVER AT GREEN ISLAND NY
Hudson River	01335500	HUDSON RIVER AT MECHANICVILLE NY
Hudson River	01329650	HUDSON RIVER AT SCHUYLERVILLE NY
Hudson River	01318000	HUDSON RIVER AT THURMAN NY
Hudson River	01328770	HUDSON RIVER AT THOMSON NY

James River	02026000	JAMES RIVER AT BENT CREEK, VA
James River	02019500	JAMES RIVER AT BUCHANAN, VA
James River	02035000	JAMES RIVER AT CARTERSVILLE, VA
James River	02037500	JAMES RIVER NEAR RICHMOND, VA
James River	02024752	JAMES RIVER AT BLUE RIDGE PKWY NR BIG ISLAND, VA
James River	02025500	JAMES RIVER AT HOLCOMB ROCK, VA
James River	02029000	JAMES RIVER AT SCOTTSVILLE, VA
James River	02016500	JAMES RIVER AT LICK RUN, VA
James River	02037000	JAMES RIVER AND KANAWHA CANAL NEAR RICHMOND, VA
James River	02025510	JAMES RIVER AT SALT CREEK, VA
Kennebec River	01046500	Kennebec River at Bingham, Maine
Kennebec River	01047150	Kennebec River near Madison, Maine
Kennebec River	01049265	Kennebec River at North Sidney, Maine
Kennebec River	01041000	KENNEBEC RIVER AT MOOSEHEAD, ME
Kennebec River	01042500	Kennebec River at The Forks, Maine
Kennebec River	01048500	KENNEBEC RIVER AT WATERVILLE, ME
Kennebec River	01049205	Kennebec River near Waterville, ME
Merrimack River	01081500	MERRIMACK RIVER AT FRANKLIN JUNCTION, NH
Merrimack River	01088500	MERRIMACK RIVER AT GARVINS FALLS, NH
Merrimack River	01092000	MERRIMACK R NR GOFFS FALLS, BELOW MANCHESTER, NH
Merrimack River	01100000	MERRIMACK RIVER BL CONCORD RIVER AT LOWELL, MA
Merrimack River	01090500	MERRIMACK RIVER AT MANCHESTER, NH
Mississippi River	05200445	MISSISSIPPI RIVER AT BEMIDJI, MN
Mississippi River	05242300	MISSISSIPPI RIVER AT BRAINERD, MN
Mississippi River	05207600	MISSISSIPPI RIVER AT WILLOW BEACH AT BALL CLUB, MN
Mississippi River	05587450	Mississippi River at Grafton, IL
Mississippi River	05283500	MISSISSIPPI RIVER AT US HWY 169 AT CHAMPLIN, MN
Mississippi River	05587455	MISSISSIPPI RIVER BELOW GRAFTON, IL
Mississippi River	05227530	MISSISSIPPI RIVER DIVERSION NEAR AITKIN, MN
Mississippi River	05288500	MISSISSIPPI RIVER AT HWY 610 IN BROOKLYN PARK, MN
Mississippi River	05331000	MISSISSIPPI RIVER AT ST. PAUL, MN
Mississippi River	05227500	MISSISSIPPI RIVER AT AITKIN, MN
Mississippi River	05200510	MISSISSIPPI RIVER NEAR BEMIDJI, MN
Mississippi River	07022000	Mississippi River at Thebes, IL
Mississippi River	05416100	MISSISSIPPI R AT LOCK & DAM 12 AT BELLEVUE, IA
Mississippi River	05344500	MISSISSIPPI RIVER AT PRESCOTT, WI
Mississippi River	05378500	MISSISSIPPI RIVER AT WINONA, MN
Mississippi River	05270700	MISSISSIPPI RIVER AT ST. CLOUD, MN
Mississippi River	05355250	MISSISSIPPI RIVER AT RED WING, MN
Mississippi River	07265450	MISSISSIPPI RIV NR ARKANSAS CITY, ARK.
Mississippi River	05261000	MISSISSIPPI RIVER NEAR FORT RIPLEY, MN
Mississippi River	07374525	Mississippi River at Belle Chasse, LA
Mississippi River	05383500	MISSISSIPPI RIVER AT LA CROSSE, WI
Mississippi River	05220500	MISSISSIPPI RIVER BELOW SANDY RIVER NR LIBBY, MN
Mississippi River	07289000	MISSISSIPPI RIVER AT VICKSBURG, MS
Mississippi River	05355250	MISSISSIPPI RIVER AT RED WING, MN
Mississippi River	05220600	MISSISSIPPI RIVER AT PALISADE, MN
Mississippi River	07020500	Mississippi River at Chester, IL
Mississippi River	05267000	MISSISSIPPI RIVER NEAR ROYALTON, MN
Mississippi River	05420500	Mississippi River at Clinton, IA
Mississippi River	05587500	Mississippi River at Alton, IL
Mississippi River	07010000	Mississippi River at St. Louis, MO
Mississippi River	05474500	Mississippi River at Keokuk, IA
Mississippi River	05211000	MISSISSIPPI RIVER AT GRAND RAPIDS, MN
Mississippi River	07047970	MISSISSIPPI RIVER AT HELENA, ARK.
Mississippi River	05275500	MISSISSIPPI RIVER AT ELK RIVER, MN
Mississippi River	05389500	Mississippi River at McGregor, IA
Mississippi River	07374000	Mississippi River at Baton Rouge, LA
Mississippi River	05331580	MISSISSIPPI RIVER BELOW L&D #2 AT HASTINGS, MN

Neuse River	02087414	0 NEUSE R TRIB AT NRWWTP (EASTERN STE) NR AUBURN, NC
Neuse River	02087500	NEUSE RIVER NEAR CLAYTON, NC
Neuse River	02087000	NEUSE RIVER NEAR NORTHSIDE, NC
Neuse River	02087570	NEUSE RIVER AT SMITHFIELD, NC
Neuse River	02087190	NEUSE RIVER NEAR NEUSE, NC
Neuse River	02087183	NEUSE RIVER NEAR FALLS, NC
Neuse River	02089500	NEUSE RIVER AT KINSTON, NC
Neuse River	02091814	NEUSE RIVER NEAR FORT BARNWELL, NC
Neuse River	02087182	0 NEUSE RIVER AT FALLS, NC
Neuse River	02087396	8 NEUSE R TRIB AT NRWWTP (CENTRAL STE) NR AUBURN, NC
Neuse River	02089000	NEUSE RIVER NEAR GOLDSBORO, NC
Neuse River	02087396	4 NEUSE R TRIB AT NRWWTP (CMP SITE) NR AUBURN, NC
Ogeechee River	02202040	OGEECHEE RIVER AT ROCKY FORD RD, NR ROCKY FORD, GA
Ogeechee River	02202680	OGEECHEE RIVER AT GA 204, NEAR ELLABELL, GA
Ogeechee River	02200120	OGEECHEE RIVER AT GA 88, NEAR GRANGE, GA
Ogeechee River	02202190	OGEECHEE RIVER AT GA 24, NEAR OLIVER, GA
Ogeechee River	02200500	OGEECHEE RIVER AT US 1, NEAR LOUISVILLE, GA
Ogeechee River	02202000	OGEECHEE RIVER AT SCARBORO, GA
Ogeechee River	02201230	OGEECHEE RIVER AT MIDVILLE, GA
Ogeechee River	02202500	OGEECHEE RIVER NEAR EDEN, GA
Pee Dee River	02135200	PEE DEE RIVER AT HWY 701 NR BUCKSPORT, SC
Pee Dee River	02131000	PEE DEE RIVER AT PEEDEE, SC
Pee Dee River	02130561	PEE DEE RIVER NR BENNETTSVILLE, SC
Pee Dee River	02131010	PEE DEE RIVER BELOW PEE DEE, SC
Pee Dee River	02129000	PEE DEE R NR ROCKINGHAM, NC
Pee Dee River	02123784	5 PEE DEE R AT HWY731 BL LK TILLERY NR NORWOOD, NC
Pee Dee River	02135210	PEE DEE R LOWER TOPSAW LANDING NR PLANTERSVILLE
Pee Dee River	02127500	PEE DEE R NR ANSONVILLE, NC
Penobscot River	01034500	Penobscot River at West Enfield, Maine
Penobscot River	01036000	PENOBSCOT RIVER AT PASSADUMKEAG, ME
Penobscot River	01036390	Penobscot River at Eddington, Maine
Penobscot River	01030000	PENOBSCOT RIVER NEAR MATTAWAMKEAG, ME
Potomac River	01613000	POTOMAC RIVER AT HANCOCK, MD
Potomac River	01646502	POTOMAC RIVER (ADJUSTED) NEAR WASH, DC
Potomac River	01618000	POTOMAC RIVER AT SHEPHERDSTOWN, WV
Potomac River	01646500	POTOMAC RIVER NEAR WASH, DC LITTLE FALLS PUMP STA
Potomac River	01610000	POTOMAC RIVER AT PAW PAW, WV
Potomac River	01638500	POTOMAC RIVER AT POINT OF ROCKS, MD
Red River	07332000	Red River near Colbert, OK
Red River	07344370	Red River at Spring Bank, AR
Red River	07316000	Red River near Gainesville, TX
Red River	07355500	RED R @ ALEXANDRIA, LA
Red River	07335500	Red River at Arthur City, TX
Red River	07337000	Red River at Index, AR
Red River	07331600	Red River at Denison Dam nr Denison, TX
Red River	07344400	Red River near Hosston, LA.
Red River	07336820	Red River near De Kalb, TX
Red River	07341500	RED RIVER AT FULTON, ARK.
Roanoke River	02054530	ROANOKE RIVER AT GLENVAR, VA
Roanoke River	02079000	ROANOKE (STAUNTON) RIVER AT CLARKSVILLE, VA
Roanoke River	02067000	ROANOKE (STAUNTON) RIVER NEAR CLOVER, VA
Roanoke River	02066000	ROANOKE (STAUNTON) RIVER AT RANDOLPH, VA
Roanoke River	02054500	ROANOKE RIVER AT LAFAYETTE, VA
Roanoke River	02062500	ROANOKE (STAUNTON) RIVER AT BROOKNEAL, VA
Roanoke River	02066500	ROANOKE CREEK AT SAXE, VA
Roanoke River	02060500	ROANOKE RIVER AT ALTAVISTA, VA
Roanoke River	02054510	ROANOKE RIVER NEAR WABUN, VA
Roanoke River	02055000	ROANOKE RIVER AT ROANOKE, VA
Roanoke River	02059000	ROANOKE RIVER NEAR GRETNA, VA
Roanoke River	02065200	ROANOKE (STAUNTON) RIVER AT CLARKTON, VA
Roanoke River	02057500	ROANOKE (STAUNTON) RIVER NEAR TOSHES, VA
Roanoke River	02056000	ROANOKE RIVER AT NIAGARA, VA
Roanoke River	02079500	ROANOKE RIVER AT BUGGS ISLAND, VA
Santee River	02171650	SANTEE RIVER BELOW ST STEPHENS, SC
Santee River	02170000	SANTEE RIVER AT FERGUSON, S. C.
Santee River	02171500	SANTEE RIVER NEAR PINEVILLE, SC

Savannah River	02198375	SAVANNAH RIVER NEAR ESTILL, SC
Savannah River	02276568	SAVANNAHS DRAINAGE CANAL AT PORT ST LUCIE FL
Savannah River	02197320	SAVANNAH R. NR JACKSON, SC
Savannah River	02187252	SAVANNAH RIVER BELOW HARTWELL LK NR HARTWELL, GA
Savannah River	02197500	SAVANNAH R AT BURTONS FERRY BR NR MILLHAVEN, GA
Savannah River	02187500	SAVANNAH RIVER NEAR IVA,S.C.
Savannah River	02197326	SAVANNAH RIVER NEAR WAYNESBORO, GA
Savannah River	02198500	SAVANNAH RIVER NEAR CLYO, GA
Savannah River	02196484	SAVANNAH RIVER NEAR NORTH AUGUSTA, SC
Savannah River	02195000	SAVANNAH RIVER NEAR CLARKS HILL, S.C.
Savannah River	02197000	SAVANNAH RIVER AT AUGUSTA, GA
Savannah River	02189000	SAVANNAH RIVER NEAR CALHOUN FALLS, S. C.
St John River	01014000	St. John River below Fish R, nr Fort Kent, Maine
St John River	01015000	ST. JOHN RIVER AT VAN BUREN, ME
St John River	01010000	St. John River at Ninemile Bridge, Maine
St John River	01012500	ST. JOHN RIVER ABOVE FISH R, AT FORT KENT, ME
St John River	01010500	St. John River at Dickey, Maine
Susquehannah River	01538700	Susquehanna River at Bloomsburg, PA
Susquehannah River	01502632	SUSQUEHANNA RIVER AT BAINBRIDGE NY
Susquehannah River	01503000	SUSQUEHANNA RIVER AT CONKLIN NY
Susquehannah River	01554000	Susquehanna River at Sunbury, PA
Susquehannah River	01513831	SUSQUEHANNA RIVER AT OWEGO NY
Susquehannah River	01515050	Susquehanna River at Sayre, PA
Susquehannah River	01536500	Susquehanna River at Wilkes-Barre, PA
Susquehannah River	01577000	Susquehanna River near McCalls Ferry, PA
Susquehannah River	01515000	SUSQUEHANNA RIVER NEAR WAVERLY NY
Susquehannah River	01576000	Susquehanna River at Marietta, PA
Susquehannah River	01497500	SUSQUEHANNA R AT COLLIERSVILLE NY
Susquehannah River	01500500	SUSQUEHANNA RIVER AT UNADILLA NY
Susquehannah River	01498620	SUSQUEHANNA RIVER SOUTHWEST OF ONEONTA NY
Susquehannah River	01513500	SUSQUEHANNA RIVER AT VESTAL NY
Susquehannah River	01531500	Susquehanna River at Towanda, PA
Susquehannah River	01578310	SUSQUEHANNA RIVER AT CONOWINGO, MD
Susquehannah River	01533400	Susquehanna River at Meshoppen, PA
Susquehannah River	01570500	Susquehanna River at Harrisburg, PA
Susquehannah River	01540500	Susquehanna River at Danville, PA
Susquehannah River	01502731	SUSQUEHANNA RIVER AT WINDSOR NY
Tar River	02081747	TAR R AT US 401 AT LOUISBURG, NC
Tar River	02084000	TAR RIVER AT GREENVILLE, NC
Tar River	02082000	TAR RIVER NEAR NASHVILLE, NC
Tar River	02083976	5 TAR RIVER TRIB BL SCHOOLHOUSE BR AT GREENVILLE
Tar River	02081500	TAR RIVER NEAR TAR RIVER, NC
Tar River	02083500	TAR RIVER AT TARBORO, NC
Tar River	02081942	TAR RIVER AT NC-581 NEAR SPRING HOPE, NC
Tar River	02081740	TAR RIVER AT LOUISBURG, NC
Tar River	02082504	0 TAR RIVER BELOW DAM NEAR LANGLEY CROSSROADS, NC
Tar River	02082506	TAR R BL TAR R RESERVOIR NR ROCKY MOUNT, NC
Tar River	02082585	TAR RIVER AT NC 97 AT ROCKY MOUNT, NC
Tar River	02083976	6 TAR RIVER TRIBUTARY AT GREENVILLE, NC
Tar River	02082610	TAR RIVER NEAR ROCKY MOUNT, NC
Tombigbee River	02449000	TOMBIGBEE RIVER AT GAINESVILLE, AL
Tombigbee River	02467000	TOMBIGBEE R AT DEMOPOLIS L&D NEAR COATOPA, AL.
Tombigbee River	02431500	TOMBIGBEE R AT BEANS FERRY NR FULTON, MS
Tombigbee River	02444500	TOMBIGBEE RIVER NEAR COCHRANE, AL.
Tombigbee River	02433500	TOMBIGBEE RIVER AT BIGBEE, MS
Tombigbee River	02441390	TOMBIGBEE RIVER AT STENNIS LOCK AND DAM, MS
Tombigbee River	02469761	TOMBIGBEE R AT COFFEEVILLE L&D NR COFFEEVILLE, AL.
Tombigbee River	02444160	TOMBIGBEE RIVER AT BEVILL L&D NR PICKENSVILLE, AL
Tombigbee River	02449500	TOMBIGBEE RIVER AT EPES, AL.
Tombigbee River	02437500	TOMBIGBEE RIVER AT ABERDEEN, MS
Tombigbee River	02447025	TOMBIGBEE R AT HEFLIN L&D NR GAINESVILLE ALA.
Tombigbee River	02431000	TOMBIGBEE RIVER NR FULTON, MS
Tombigbee River	02470000	TOMBIGBEE RIVER NEAR LEROY, AL.

Table S3. List of all USGS sites whose river discharge data were used in this study.

Region	Variable	NAO	HNAO	AMO	HAMO	ENSO	HENSO	PDO	HPDO
GME	Sea level	**Yes**	**Yes**	No	**Yes**	No	**Yes**	No	No
GME	River discharge	No	No	No	No	No	No	No	No
MAB	Sea level	No	No	No	**Yes**	No	**Yes**	No	No
MAB	River discharge	No	No	No	No	No	No	No	No
SAB	Sea level	**Yes**	No	No	No	No	No	No	No
SAB	River discharge	No	No	No	No	**Yes**	Yes	**Yes**	No
GMX	Sea level	**Yes**	No	No	No	No	**Yes**	No	No
GMX	River discharge	No	No	**Yes**	No	No	No	No	No

Table S4. Table showing which climate modes (NAO, AMO, ENSO, PDO) and their Hilbert transforms (HNAO, HAMO, HENSO, HPDO) are significantly correlated with each of the regional river-discharge or sea-level time series. The regional acronyms are: GME (Gulf of Maine), MAB (Mid-Atlantic Bight), SAB (South Atlantic Bight), and GMX (Gulf of Mexico).