

# Evidence for global runoff increase related to climate warming

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## Abstract

Ongoing global climatic change initiated by the anthropogenic release of carbon dioxide is a matter of intense debate. We focus both on the impact of these climatic changes on the global hydrological cycle and on the amplitude of the increase of global and continental runoff over the last century, in relation to measured temperature increases. In this contribution, we propose an original statistical wavelet-based method for the reconstruction of the monthly discharges of worldwide largest rivers. This method provides a data-based approximation of the evolution of the annual continental and global runoffs over the last century. A consistent correlation is highlighted between global annual temperature and runoff, suggesting a 4% global runoff increase by 1  C global temperature rise. However, this global trend should be qualified at the regional scale where both increasing and decreasing trends are identified. North America runoffs appear to be the most sensitive to the recent climatic changes. Finally, this contribution provides the first experimental data-based evidence demonstrating the link between the global warming and the intensification of the global hydrological cycle. This corresponds to more intense evaporation over oceans coupled to continental precipitation increase or continental evaporation decrease. This process finally leads to an increase of the global continental runoff.

*Keywords:* Climate change; Global runoff; Runoff-temperature relationship; Wavelet analysis

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## 1. Motivations and objectives

Recent studies have shown that global mean temperature increases may have a serious impact on the global hydrological cycle at various spatial and temporal scales. A large and complete review of the most recent trends in hydrological changes related to global climate warming can be found in the IPCC 2001 report [18] [Chapter 4]. Two main effects are identified: increasing risk of floods [33] and droughts at local or regional scales and increase or decrease of water availability at the continental scale [43].

A large majority of these studies are based on outputs from simulations performed with GCMs or OAGCMs coupled to various distributed models of surface and subsurface hydrologic processes [13,32,34,35].

An alternative approach consists of an extensive analysis of the possible correlation between measured

climate and hydrological parameters such as precipitation, runoff or temperature [10,12,24]. However, these studies usually deal with local or regional time series. Since Probst and Tardy's work [38,39], no recent global, data-based study has focused on possible global hydrological changes related to recent climate changes.

Powerful tools to perform such global and long term ( $10^1$ – $10^2$  years) analysis are the stream flows of large rivers draining  $10^5$ – $10^6$  km<sup>2</sup>, since they integrate rainfall, evaporation, topography, lithology, soil, and vegetation cover heterogeneities. However, the length and reliability of the available time series are highly variable. Moreover, gaps are usually found within the time series. Finally, the impact of dams or irrigation on the natural hydrological regime of rivers must be identified and anthropogenic effects must be removed. Such discrepancies between the various time series require the use of a pertinent method to complete or reconstruct runoff time series, prior to performing any analysis of global or continental long term runoff evolution. Then, in order to estimate missing runoff, we introduce a novel statistical wavelet method based on a reduced number of long-term large river runoff series. Wavelets are preferred to

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classical correlation methods since they integrate the hydrological multi-scale variability.

## 2. Data

Previous studies of the global runoff fluctuations were based on a rather limited numbers of rivers [36,38,39]. In this contribution, the database is extended to 221 rivers: 66 North American rivers including the St. Lawrence, Colorado, Columbia, Ohio, Nelson and Mac Kenzie, 51 Asian rivers including the Mekong, Amur, Ob, Yenisey, Lena, Chang Jiang and Volga, 40 European rivers including the Danube, Northern Dvina and Elbe, 33 South American rivers including the Amazon, Parana, Orinoco and Tocantins and 31 African rivers including the Nile, Congo, Niger and Zambezi. The surface area of the gauging reference stations ranges from  $10^4$  to  $4.5 \times 10^6$  km<sup>2</sup>, latitude position ranges from 40.3 S to 72.37 N and longitude position ranges from -158.1 W to 184 E. Indeed, river discharges have been measured in some cases for only a few decades, while others have been sampled back to 1870. Sampling periods for the different rivers ranges from 4 to 182 years.

An exhaustive list of the selected rivers is given continent by continent in Tables 1–3. For each river, the watershed extend, the geographical localisation of the hydrometric station and the sampling interval are mentioned.

The Global Runoff Data Center and the Unesco River Discharge Database [42] provide most of the discharge data from selected rivers distributed all around the world (Fig. 1). Amazon discharges are provided by the Hybam Database (ANA, UNB, IRD). The most complete time series are available for North America and Europe.

A monthly sampling rate is used as it allows a precise study of the different time-scale fluctuations of the discharge of these large rivers, from monthly and seasonal to interannual fluctuations. This multi-scale behaviour of large river runoffs corresponding to multi-scale climate forcings justifies the introduction of a time-scale decomposition provided by wavelet methods [25,26].

Based on Baumgartner and Reichel estimations [2], the dataset roughly corresponds to 58% of the total African runoff, 46% of the total Asian runoff, 43% of the total European runoff, 44% of the total North American runoff, 80% of the total South American runoff, and 51% of the global runoff. By comparison, Probst et Tardy based their global reconstitution on 50 rivers corresponding to 13% of the global runoff.

## 3. Reconstruction method of the monthly river discharges

The key difficulty encountered in the analysis of the fluctuations in the runoff of large rivers is the multi-scale property of the signal in relation to several hydrological

processes. Monthly fluctuations generally reflect the occurrence of low or high intensity events. Annual fluctuations record the variations of the annual water budget highlighting dry and humid years. *Multi-annual* fluctuations reflect the largest scale variations related to global general meteorological circulations and long term climate change. Among the different techniques widely used nowadays, wavelet and multi-resolution [11,16,29] analyses propose a time-scale transformation of the signal that accounts for flow variability. These methods have already been applied in different fields of hydrology ([9,14,22,23,25–27] and references therein).

## 4. Overview of the wavelet transform

The basic objective of the wavelet transform is to achieve a complete time-scale (or shift-scale) representation of localized and transient phenomena occurring at different time scales. In the wavelet transform, the Fourier basis is replaced by a two-parameter basis  $\{\psi_{a,\tau}(t), (a, \tau) \in (R_+^* \times R)\}$  where “ $a$ ” is the scale, and “ $\tau$ ” is time-shift. This allows a time-scale discrimination of processes. The coefficients of the wavelet transform of a continuous-time signal  $x(t)$  are defined by the linear integral convolution operator:

$$C_x(a, \tau) = \int_{-\infty}^{+\infty} x(t)\psi_{a,\tau}^*(t) dt \quad \text{with} \quad \psi_{a,\tau}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-\tau}{a}\right) \quad (1)$$

where  $*$  corresponds to the complex conjugate. The function  $\psi(t)$  is called a wavelet. The parameter “ $a$ ” can be interpreted as a dilation ( $a > 1$ ) or contraction ( $a < 1$ ) factor of the wavelet function  $\psi(t)$ , corresponding to different scales of observation. The parameter “ $\tau$ ” can be interpreted as a temporal translation or shift of the function  $\psi(t)$ , which allows the study of the signal  $x(t)$  locally around the time  $\tau$ . Actual hydrological signals are discrete in time. Then, both the time shift ( $\tau$ ) and the “scale” domain (“ $a$ ”) are also discretized. The discretized version of Eq. (1) defines the discrete wavelet transform coefficients as follows:

$$C_x(j, k) = \int_{-\infty}^{+\infty} x(t)\psi_{j,k}^*(t) dt \quad \text{with} \quad \psi_{j,k}(t) = a_0^{j/2}\psi(a_0^j t - k\tau_0) \quad (2)$$

where  $*$  corresponds to the complex conjugate. The integer “ $j$ ” is the scale factor, analogous to the “ $a$ ” parameter of Eq. (1) and the integer “ $k\tau_0$ ” is the translation factor analogous to the “ $\tau$ ” parameter. If one takes  $a_0 = 2$  and  $\tau_0 = 1$ , the continuous scale-time grid is replaced by a discrete dyadic grid of the form:  $(\{2^{-j}, k.2^{-j}\}, (k, j) \in Z^2)$ . The orthogonal discrete wavelet transform coefficients  $C_{j,k}$  are then defined by the convolution product:

Table 1

Name, watershed area, geographical localisation and discharge series extend of the selected rivers over Africa (Panel A) and Asia (Panel B)

| River                  | Area      | Lat     | Long   | From | To   |
|------------------------|-----------|---------|--------|------|------|
| <i>Panel A: Africa</i> |           |         |        |      |      |
| Nile                   | 2,870,000 | 23.96   | 32.90  | 1870 | 1980 |
| Senegal                | 268,000   | 16.52   | -15.5  | 1952 | 1989 |
| Niger                  | 1,000,000 | 11.87   | 3.38   | 1953 | 1980 |
| Congo-Zaire            | 3,475,000 | -4.3    | 15.3   | 1903 | 1984 |
| Tana                   | 42,217    | -0.45   | 39.70  | 1934 | 1976 |
| Sanaga                 | 131,520   | 3.76    | 10.07  | 1944 | 1980 |
| Oranje                 | 850,530   | -28.71  | 17.73  | 1965 | 1987 |
| Zambezi                | 940,000   | -16.15  | 33.58  | 1976 | 1980 |
| Moulouya               | 24,422    | 34.24   | -3.32  | 1959 | 1989 |
| Rufiji                 | 158,200   | -7.8    | 37.92  | 1955 | 1963 |
| Ogooue                 | 203,500   | 0.68    | 10.23  | 1954 | 1976 |
| Volta                  | 394,100   | 6.2     | 0.10   | 1936 | 1964 |
| Save River             | 100,885   | -21.1   | 34.68  | 1976 | 1980 |
| Limpopo                | 342,000   | -24.54  | 33.00  | 1976 | 1980 |
| Shebele                | 272,700   | 2.37    | 45.42  | 1954 | 1970 |
| Nyong                  | 26,400    | 3.57    | 10.12  | 1951 | 1977 |
| Mangoky                | 53,225    | -21.83  | 43.87  | 1965 | 1976 |
| Cavally                | 28,800    | 4.38    | -7.59  | 1971 | 1997 |
| Bandama                | 95,500    | 5.88    | -4.75  | 1970 | 1997 |
| Sassandra              | 62,000    | 5.76    | -6.60  | 1977 | 1997 |
| Comoe                  | 69,900    | 6.28    | -3.49  | 1970 | 1988 |
| Kouilou                | 55,010    | -4.1    | 12.07  | 1969 | 1983 |
| Benue                  | 107,000   | 9.25    | 12.50  | 1960 | 1990 |
| Incomati               | 37,600    | -25.02  | 32.73  | 1976 | 1980 |
| Maputo                 | 28,500    | -26.78  | 32.43  | 1976 | 1980 |
| Shire                  | 149,500   | -16.549 | 35.13  | 1953 | 1982 |
| Pangani                | 25,110    | -5.17   | 38.47  | 1971 | 1979 |
| Tugela                 | 28,920    | -29.139 | 31.39  | 1965 | 1973 |
| Oueme                  | 46,990    | 6.90    | 2.45   | 1963 | 1981 |
| Juba                   | 179,520   | 3.56    | 42.32  | 1951 | 1968 |
| <i>Panel B: Asia</i>   |           |         |        |      |      |
| Mekong                 | 391,000   | 16.53   | 104.73 | 1925 | 1987 |
| Godavari               | 299,320   | 16.92   | 81.78  | 1902 | 1961 |
| Indigirka              | 305,000   | 69.58   | 147.35 | 1937 | 1992 |
| Kamchatka              | 51,600    | 56.27   | 161.67 | 1941 | 1988 |
| Ural                   | 308,000   | 50.85   | 51.28  | 1921 | 1985 |
| Amur                   | 1,730,000 | 50.63   | 137.12 | 1933 | 1985 |
| Ob                     | 2,430,000 | 66.57   | 66.53  | 1930 | 1995 |
| Yenisey                | 2,440,000 | 67.48   | 86.50  | 1936 | 1996 |
| Maya                   | 165,000   | 59.75   | 134.75 | 1965 | 1985 |
| Kolyma                 | 361,000   | 67.37   | 153.67 | 1934 | 1958 |
| Lena                   | 2,460,000 | 72.37   | 126.80 | 1951 | 1995 |
| Yana                   | 216,000   | 69.77   | 135.23 | 1938 | 1985 |
| Alazeja                | 29,000    | 69.17   | 154.50 | 1978 | 1994 |
| Bramaputra             | 636,130   | 25.18   | 89.67  | 1972 | 1976 |
| Chang Jiang            | 1,705,383 | 30.76   | 117.62 | 1950 | 1987 |
| Ganges                 | 935,000   | 25      | 87.92  | 1965 | 1974 |
| Huang He               | 730,036   | 34.92   | 113.65 | 1949 | 1989 |
| Indus                  | 832,418   | 25.37   | 68.37  | 1975 | 1980 |
| Krishna                | 251,355   | 16.52   | 80.62  | 1901 | 1961 |
| Mahanadi               | 132,090   | 20.42   | 83.67  | 1965 | 1971 |
| Narmada                | 89,345    | 21.92   | 73.65  | 1949 | 1961 |
| Penzhina               | 71,600    | 62.42   | 166.03 | 1968 | 1985 |
| Pur                    | 95,100    | 67.00   | 78.22  | 1939 | 1978 |
| Xi Jiang               | 329,705   | 23.48   | 111.30 | 1946 | 1985 |
| Nadym                  | 48,000    | 65.62   | 72.67  | 1968 | 1992 |
| Taz                    | 100,000   | 66.59   | 82.28  | 1962 | 1984 |
| Olenek                 | 198,000   | 72.12   | 123.22 | 1953 | 1991 |
| Anabar                 | 78,500    | 71.98   | 193.95 | 1966 | 1995 |
| Anadyr                 | 47,300    | 65.08   | 169.00 | 1965 | 1985 |
| Volga                  | 1,360,000 | 48.77   | 44.72  | 1879 | 1936 |

(continued on next page)

Table 1 (continued)

| River      | Area    | Lat   | Long   | From | To   |
|------------|---------|-------|--------|------|------|
| Yongding   | 42,500  | 40.23 | 115.60 | 1949 | 1956 |
| Luanhe     | 44,100  | 39.73 | 118.75 | 1946 | 1989 |
| Huaihe     | 121,330 | 32.93 | 117.38 | 1950 | 1987 |
| Beijiang   | 34,013  | 23.85 | 113.27 | 1954 | 1988 |
| Dongjiang  | 25,325  | 23.17 | 114.30 | 1960 | 1988 |
| Irrawady   | 117,900 | 21.97 | 96.1   | 1978 | 1989 |
| Karkheh    | 45,882  | 31.47 | 48.42  | 1976 | 1980 |
| Euphrates  | 274,100 | 32.72 | 44.27  | 1965 | 1973 |
| Tigris     | 134,000 | 33.3  | 44.38  | 1965 | 1973 |
| Han        | 25,046  | 37.52 | 126.97 | 1955 | 1973 |
| Mahi       | 33,670  | 22.3  | 73.03  | 1968 | 1980 |
| Tapi       | 61,575  | 21.28 | 72.95  | 1965 | 1980 |
| Penner     | 53,290  | 14.45 | 79.98  | 1965 | 1975 |
| Cauvery    | 74,000  | 10.83 | 78.83  | 1976 | 1980 |
| Omoloy     | 108,000 | 69.38 | 134.62 | 1979 | 1994 |
| Syr-Darya  | 219,000 | 44.05 | 67.05  | 1949 | 1985 |
| Amu-Darya  | 450,000 | 42.28 | 59.70  | 1938 | 1974 |
| Chao Praya | 110,569 | 15.67 | 100.12 | 1976 | 1994 |
| Chindwin   | 27,420  | 26    | 95.70  | 1978 | 1989 |
| Karun      | 60,769  | 31.32 | 48.67  | 1965 | 1971 |
| Bol Anui   | 49,600  | 68.15 | 161.17 | 1978 | 1989 |

$$C_{j,k}^x = \int_{-\infty}^{+\infty} x(t)\psi_{j,k}^*(t) dt \quad \text{with} \quad \psi_{j,k}(t) = 2^{j/2}\psi(2^j t - k) \quad (3)$$

To sum up, the multi-resolution analysis allows an orthogonal decomposition of a sampled hydrological signal in term of approximation and details of increasing order of resolution.

## 5. Reconstruction method

The proposed global and continental runoff reconstruction is based on reference runoff series selected among the overall database in relation to their high reliability over long period (several decades). Anthropogenic effects are first removed by truncation. For instance, *Nile* discharges after Assam Dam construction are removed. It should be noted that these reference series consist in a reduced number of ten reference rivers.

The multi-resolution analysis of river discharge series is based on a Daubechies D20 wavelet, since this wavelet constitutes in general the optimal orthogonal wavelet representation for runoff series [25,26]. The multi-resolution is implemented using classical multi-resolution MATLAB algorithm described in [25,26].

The multi-resolution analysis of the reference runoff series defines three “hydrological” reference components (month, annual and *multi-annual*). For example, the annual component corresponds to the classical recharge–discharge process. Then, for each rivers, a three-step reconstruction method estimates missing monthly runoffs.

The first step identifies the three “hydrological” components (month, annual and *multi-annual*) through multi-resolution analysis of each non-reference runoff series. For each hydrological component, the second step consists in the determination for each time series of the reference river characterized by as similar as possible fluctuations, possibly delayed in time. The maximum of the cross-correlation function between the considered runoff series and each reference rivers are calculated. The “optimum” reference river and the “optimum” delay for each scales (month, annual and pluri-annual) corresponds to the highest cross-correlation value. The missing values are estimated in a third step. For each time-scale component, missing values are estimated using a linear regression with the “optimum” reference river. The summation of the three components leads to an estimation of the reconstructed discharges. This method provides a qualitative reconstruction of the runoff’s temporal structure. To provide both similar temporal variability and frequency distributions between the reconstructed and the observed time series, mean, variance and probability density distribution are calibrated on to the observed values.

At monthly scales, mean correlation coefficients are respectively 0.45 and  $-0.37$ . That indicates that a simple regression analysis based on monthly runoffs may lead to poor results. At large scales, mean correlation coefficients are respectively 0.48 and  $-0.39$ . Finally, the main improvement of this method compared to a simple regression analysis lies in the quality of the annual components rivers reconstruction (Fig. 2). Mean annual correlation coefficients are respectively 0.8 and  $-0.78$  with a maximum of correlation observed at the highest latitudes.

Table 2

Name, watershed area, geographical localisation and discharge series extend of the selected rivers Europe

| River          | Area    | Lat   | Long  | From | To   |
|----------------|---------|-------|-------|------|------|
| Garonne        | 52,000  | 44.42 | 0.23  | 1921 | 1980 |
| Loire          | 110,000 | 47.38 | -0.83 | 1863 | 1980 |
| Guadalquivir   | 46,995  | 37.52 | -5.98 | 1913 | 1964 |
| Seine          | 44,320  | 48.83 | 2.27  | 1928 | 1965 |
| Rhone          | 95,590  | 43.92 | 4.67  | 1921 | 1980 |
| Ebre           | 84,230  | 40.82 | 0.52  | 1913 | 1965 |
| Vuoksi         | 61,275  | 61.15 | 28.78 | 1847 | 1985 |
| Elbe           | 131,950 | 5.24  | 10.89 | 1875 | 2000 |
| Vistule        | 194,376 | 54.09 | 18.82 | 1901 | 1994 |
| Oder           | 109,729 | 52.76 | 14.32 | 1901 | 1994 |
| Danube         | 807,000 | 45.18 | 28.73 | 1921 | 2000 |
| Jucar          | 17,876  | 39.11 | -0.65 | 1913 | 1966 |
| Tiber          | 16,545  | 41.9  | 12.48 | 1921 | 1980 |
| Western Dvina  | 64,600  | 55.88 | 26.68 | 1965 | 1985 |
| Po             | 70,091  | 44.88 | 11.65 | 1918 | 1986 |
| Rhine          | 159,680 | 51.76 | 6.40  | 1854 | 2000 |
| Vannern-Gota   | 46,830  | 58.38 | 12.32 | 1807 | 1966 |
| Weser          | 37,790  | 52.96 | 9.13  | 1857 | 2000 |
| Dnestr         | 66,100  | 46.8  | 29.37 | 1965 | 1985 |
| Dnieper        | 463,000 | 47.92 | 35.15 | 1952 | 1985 |
| Drava          | 37,142  | 45.78 | 18.20 | 1921 | 1974 |
| Mezen          | 56,400  | 65.00 | 45.62 | 1921 | 1994 |
| Northern Dvina | 348,000 | 64.1  | 42.17 | 1882 | 1994 |
| Neva           | 281,000 | 59.8  | 30.72 | 1859 | 1989 |
| Don            | 378,000 | 47.5  | 40.67 | 1891 | 1953 |
| Kemi           | 50,790  | 65.95 | 24.7  | 1911 | 1985 |
| Kymijoki       | 36,535  | 60.8  | 26.82 | 1939 | 1993 |
| Glomma         | 10,243  | 59.36 | 11.07 | 1902 | 1973 |
| Neman          | 81,200  | 55.01 | 22.52 | 1812 | 1994 |
| Petchora       | 248,000 | 65.42 | 52.28 | 1932 | 1985 |
| Douro          | 91,491  | 41.15 | -7.68 | 1933 | 1969 |
| Tejo           | 67,490  | 39.47 | -8.37 | 1976 | 1982 |
| Guadania       | 60,833  | 37.82 | -7.63 | 1948 | 1990 |
| Angerman       | 30,640  | 63.17 | 17.27 | 1965 | 1999 |
| Kokemkenjoki   | 26,025  | 61.35 | 22.12 | 1931 | 1993 |
| Kenijoki       | 50,900  | 65.78 | 24.55 | 1949 | 1993 |
| Narva          | 56,000  | 59.35 | 28.25 | 1956 | 1992 |
| Southern Bug   | 46,200  | 47.72 | 31.18 | 1965 | 1985 |
| Kuban          | 48,100  | 45.15 | 38.32 | 1965 | 1985 |
| Kura           | 178,000 | 40.12 | 48.67 | 1930 | 1985 |

Reconstructed discharge time series are summed up continent by continent and a weighting coefficient based on the estimation of global and continental mean annual performed by Baumgartner and Reichel is applied to account for the complete continental surface. Finally, estimation of the global runoff is achieved by applying a 1/0.89 coefficient to account for the Australian and Antarctic continents contribution.

## 6. Variability of the reconstructed global runoffs

“Year to year” mean fluctuations of the reconstructed continental runoffs display a succession of dry and humid periods (Fig. 2). African runoff is characterized by a long dry period from 1900 to 1960 contrasting with intense humid periods occurring around 1890 and 1965.

Asian runoff shows a periodic succession of dry and humid periods. This 15 year periodic signal presents a constant 10-year delay with the African runoff. North American runoff is characterized by a dry period between 1910 and 1940 followed by a regular succession of 10-year long humid and dry periods. This pattern shows also a rough 10-year shift compared to European runoff for the 1920–1980 period. South American runoff displays a rapid succession of dry and humid periods for the 1890–1945 interval. North American and Asian runoff exhibit similar fluctuations, roughly in opposition with the European behaviour. African and South American continental runoff appear as quite disconnected from others signals for the complete reconstruction period.

Global runoff fluctuations show a long dry period between 1900 and 1940 followed by a succession of

Table 3

Name, watershed area, geographical localisation and discharge series extend of the selected rivers over North America (Panel A) and South America (Panel B) and Australia (Panel C)

| River                         | Area      | Lat   | Long    | From | To   |
|-------------------------------|-----------|-------|---------|------|------|
| <i>Panel A: North America</i> |           |       |         |      |      |
| St. Lawrence                  | 764,600   | 45.01 | -74.79  | 1861 | 1984 |
| Red River                     | 104,000   | 49    | -97.22  | 1913 | 1985 |
| Assiniboine                   | 153,000   | 49.86 | -97.40  | 1913 | 1985 |
| North Saskatchewan            | 131,000   | 53.2  | -105.77 | 1912 | 1985 |
| South Saskatchewan            | 141,000   | 52.13 | -106.65 | 1912 | 1970 |
| Susquehanna                   | 62,419    | 40.25 | -76.88  | 1891 | 1984 |
| Niagara                       | 686,000   | 43.15 | -79.05  | 1860 | 1985 |
| San Pedro                     | 25,800    | 21.97 | -105.15 | 1976 | 1981 |
| Fuerte                        | 34,247    | 25.95 | -109.05 | 1976 | 1982 |
| St. Marys                     | 210,000   | 46.51 | -84.37  | 1860 | 1911 |
| Winnipeg                      | 126,000   | 50.22 | -95.57  | 1908 | 1985 |
| Colorado River                | 289,562   | 36.86 | -111.59 | 1911 | 1966 |
| Mississippi                   | 444,185   | 38.88 | -90.18  | 1928 | 1985 |
| Ohio                          | 525,770   | 37.15 | -88.74  | 1928 | 1985 |
| Columbia                      | 613,830   | 45.61 | -121.17 | 1879 | 1974 |
| Yaqui                         | 57,908    | 28.93 | -109.62 | 1976 | 1980 |
| Hudson                        | 20,953    | 42.75 | -73.69  | 1947 | 1984 |
| Delware                       | 17,560    | 40.21 | -74.78  | 1913 | 1985 |
| Potomac                       | 29,940    | 38.96 | -77.12  | 1931 | 1985 |
| Alabama                       | 56,980    | 31.53 | -87.52  | 1931 | 1960 |
| Yukon                         | 264,000   | 64.06 | -139.43 | 1966 | 1996 |
| Nelson                        | 1,000,000 | 54.76 | -97.92  | 1966 | 1985 |
| Bravo                         | 459,902   | 25.9  | -97.52  | 1976 | 1980 |
| Athabasca                     | 133,000   | 56.78 | -111.4  | 1966 | 1985 |
| Miles Iles                    | 146,000   | 45.54 | -73.87  | 1927 | 1961 |
| Panuco                        | 58,115    | 21.98 | -98.57  | 1965 | 1980 |
| Santiago                      | 122,960   | 21.82 | -105.12 | 1965 | 1982 |
| Usumacinta                    | 47,697    | 17.43 | -91.5   | 1969 | 1984 |
| Back                          | 93,900    | 66.08 | -96.5   | 1965 | 1997 |
| Fraser                        | 217,000   | 49.38 | -121.45 | 1913 | 1997 |
| MacKenzie                     | 1,570,000 | 65.28 | -126.85 | 1966 | 1997 |
| Moose river                   | 60,100    | 50.81 | -81.3   | 1966 | 1985 |
| Slave River                   | 606,000   | 59.86 | -111.58 | 1960 | 1985 |
| Stikine River                 | 29,300    | 57.9  | -131.15 | 1965 | 1985 |
| Altamaha                      | 35,224    | 31.65 | -81.83  | 1932 | 1985 |
| Apalachicola                  | 44,548    | 30.7  | -84.86  | 1930 | 1985 |
| Brazos                        | 116,568   | 29.58 | -95.76  | 1923 | 2000 |
| Copper                        | 53,354    | 61.46 | -144.45 | 1956 | 1985 |
| Klamath                       | 31,339    | 41.51 | -124    | 1951 | 1995 |
| Kuskowim                      | 80,549    | 61.86 | -158.1  | 1952 | 1994 |
| Susitna                       | 50,246    | 61.54 | -150.51 | 1975 | 1993 |
| Quachita                      | 39,622    | 32.5  | -92.13  | 1965 | 1976 |
| San Joaquin                   | 35,058    | 37.67 | -121.26 | 1930 | 2000 |
| Connecticut                   | 25,019    | 41.98 | -72.6   | 1929 | 2000 |
| Nueces                        | 43,149    | 28.04 | -97.86  | 1940 | 2000 |
| Trinity                       | 44,512    | 30.43 | -94.85  | 1925 | 2000 |
| Skeena                        | 42,200    | 54.63 | -128.43 | 1939 | 1997 |
| Peel River                    | 70,600    | 67.25 | -134.88 | 1975 | 1994 |
| Anderson River                | 56,300    | 68.63 | -128.41 | 1970 | 1994 |
| Baleine River                 | 43,200    | 55.28 | -77.58  | 1963 | 1993 |
| Melezes River                 | 42,700    | 57.67 | -69.61  | 1963 | 1982 |
| Thelon River                  | 65,300    | 64.53 | -101.4  | 1972 | 1997 |
| Attawapiskat                  | 36,000    | 53.1  | -87.08  | 1968 | 1994 |
| Kazan River                   | 72,300    | 63.65 | -95.85  | 1972 | 1997 |
| Winisk                        | 50,000    | 54.52 | -87.23  | 1983 | 1995 |
| Albany River                  | 118,000   | 51.33 | -83.87  | 1972 | 1995 |
| Grande Riviere                | 96,300    | 53.73 | -78.57  | 1960 | 1978 |
| Savannah                      | 25,511    | 32.53 | -81.26  | 1938 | 2000 |
| River aux Feuilles            | 41,700    | 58.64 | -70.42  | 1963 | 1987 |
| Riviere George                | 35,200    | 58.15 | -65.84  | 1963 | 1970 |
| Quoich River                  | 30,100    | 64.31 | -93.9   | 1972 | 1980 |

Table 3 (continued)

| River                         | Area      | Lat    | Long    | From | To   |
|-------------------------------|-----------|--------|---------|------|------|
| Seal River                    | 48,100    | 58.89  | -96.27  | 1955 | 1988 |
| Severn River                  | 94,300    | 55.37  | -88.32  | 1983 | 1995 |
| Nottaway                      | 57,500    | 50.13  | -77.41J | 1961 | 1982 |
| Rupert                        | 40,900    | 51.45  | -76.87  | 1964 | 1995 |
| Eastmain                      | 44,300    | 52.25  | -78.07  | 1960 | 1980 |
| <i>Panel B: South America</i> |           |        |         |      |      |
| Parana                        | 2,300,000 | -27.46 | -58.85  | 1905 | 1983 |
| Sab Francisco                 | 510,800   | -9.41  | -40.52  | 1929 | 1980 |
| Amazonia                      | 4,500,000 | -1.91  | -55.50  | 1903 | 1998 |
| Paraiba do Sul                | 55,083    | -21.75 | -41.33  | 1928 | 1992 |
| Magdalena                     | 257,438   | 10.26  | -74.92  | 1976 | 1980 |
| Uruguay                       | 249,312   | -31.95 | -58.02  | 1969 | 1980 |
| Tocatins                      | 727,900   | -5.13  | -49.35  | 1970 | 1982 |
| Negro                         | 95,000    | -40.43 | -63.67  | 1973 | 1980 |
| Jequitinhonha                 | 62,365    | -16.13 | -40.3   | 1943 | 1979 |
| Rio Parnaiba                  | 282,000   | -3.43  | -42.5   | 1976 | 1982 |
| Orinoco                       | 836,000   | 8.14   | -63.6   | 1925 | 1990 |
| Salado                        | 40,000    | -26.22 | -63.75  | 1935 | 1980 |
| Jachal                        | 25,500    | -30.22 | -68.83  | 1937 | 1980 |
| San Juan                      | 25,000    | -31.52 | -68.63  | 1910 | 1980 |
| Rio Prado                     | 30,360    | -15.57 | -39.28  | 1937 | 1970 |
| Cuyuni                        | 53,400    | 6.43   | -58.82  | 1973 | 1982 |
| Essequibo                     | 66,600    | 5.84   | -58.58  | 1965 | 1992 |
| Corantijn                     | 51,600    | 5.8    | -57.12  | 1973 | 1980 |
| Maroni                        | 63,700    | 4.98   | -54.43  | 1976 | 1980 |
| Negro                         | 63,000    | -33.12 | -57.18  | 1952 | 1980 |
| Oyapock                       | 25,120    | 3.82   | -51.88  | 1954 | 1996 |
| Xingu                         | 446,570   | -3.2   | -52.22  | 1972 | 1995 |
| Rio Jari                      | 51,345    | -0.68  | -52.55  | 1973 | 1986 |
| Rio Paru de Este              | 30,945    | -0.42  | -53.7   | 1973 | 1989 |
| Rio Capim                     | 38,178    | -2.51  | -47.82  | 1972 | 1987 |
| Rio Gurupi                    | 31,850    | -1.83  | -46.22  | 1974 | 1986 |
| Rio Pindare                   | 34,300    | -3.66  | -45.46  | 1972 | 1992 |
| Rio Mearim                    | 25,500    | -4.21  | -44.76  | 1976 | 1992 |
| Rio Itapecuru                 | 50,800    | -3.63  | -44.38  | 1969 | 1992 |
| Rio Parnaiba                  | 322,823   | -3.45  | -42.37  | 1982 | 1993 |
| Rio Jaguaribe                 | 48,200    | -5.219 | -38.2   | 1967 | 1983 |
| Rio Paraguacu                 | 31,488    | -12.52 | -39.87  | 1967 | 1979 |
| Rio de Contas                 | 42,245    | -13.88 | -40.1   | 1954 | 1978 |
| Rio Tapajos                   | 358,657   | -6.03  | -57.6   | 1985 | 1995 |
| <i>Panel C: Australia</i>     |           |        |         |      |      |
| Burdekin                      | 129,660   | -19.76 | 147.24  | 1951 | 1993 |
| Fitzroy                       | 136,650   | -23.14 | 150.37  | 1915 | 1951 |
| Mitchell                      | 46,050    | -18.95 | 142.38  | 1973 | 1988 |
| Murray                        | 991,000   | -34.18 | 141.6   | 1973 | 1985 |
| Emu Spring                    | 82,300    | -27.85 | 114.54  | 1968 | 1997 |
| Nune Mile                     | 73,400    | -24.82 | 113.77  | 1958 | 1997 |
| Nanutarra                     | 70,200    | -22.54 | 115.489 | 1973 | 1996 |
| Jimbegnyinoo                  | 48,900    | -21.32 | 116.15  | 1969 | 1995 |
| Coolenar                      | 49,600    | -20.31 | 119.235 | 1975 | 1995 |
| Coolibah                      | 44,900    | -15.52 | 130.945 | 1970 | 1996 |

15-year long dry and humid periods. A 65–70 year-long term process is also identified [40]. Compared to previous estimates this global runoff reconstruction displays more pronounced amplitudes of dry and humid periods.

In order to compare our results with previous study [38,39] which focused over the 1900–1975 period, trends have been calculated for two reference periods: 1900–1975 and 1925–1994 so that recent changes corre-

sponding to the recent increase in temperature are emphasized (Fig. 3).

Effectively, over the first period, the linear regression between global runoff ( $R_{\text{GLOBAL}}$  in  $10^{16}$  l/year) versus time lead to  $R_{\text{GLOBAL}} \propto 41.47 \times 10^{-5} t$ , whereas on the second period  $R_{\text{GLOBAL}} \propto 112.24 \times 10^{-5} t$ .

Global runoff values exhibit the same increase as mentioned in [38,39] for the 1900–1975 period (mean

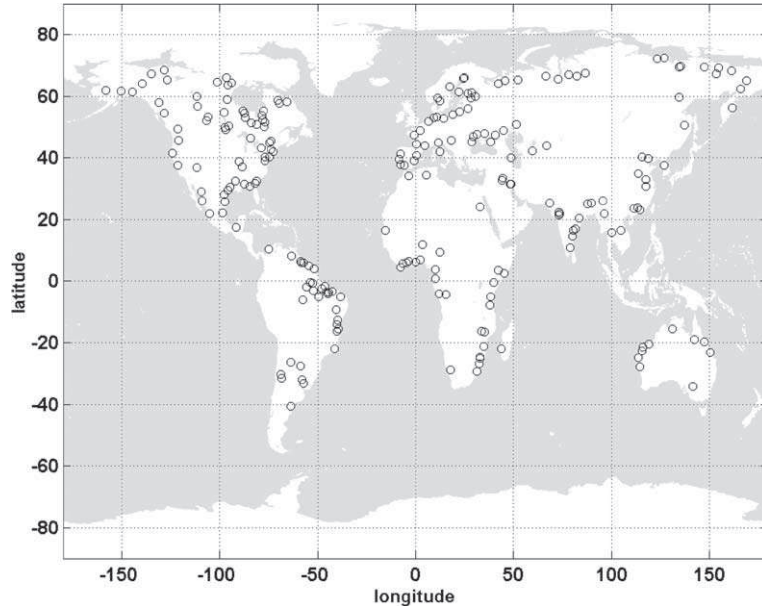


Fig. 1. Geographical location of the 231 stations considered in the continental and global runoff reconstruction process. Spatial repartition of the gauging stations appears homogeneous and globally follows the latitudinal distribution of continents, given that 46 rivers are located in the southern hemisphere and 185 rivers in the northern hemisphere. Surface area of the gauging reference stations ranges from  $10^4$  to  $4.5 \times 10^6$  km<sup>2</sup>, latitude and longitude position ranges respectively from 40.3 S to 72.37 N and  $-158.1$  W to 184 E.

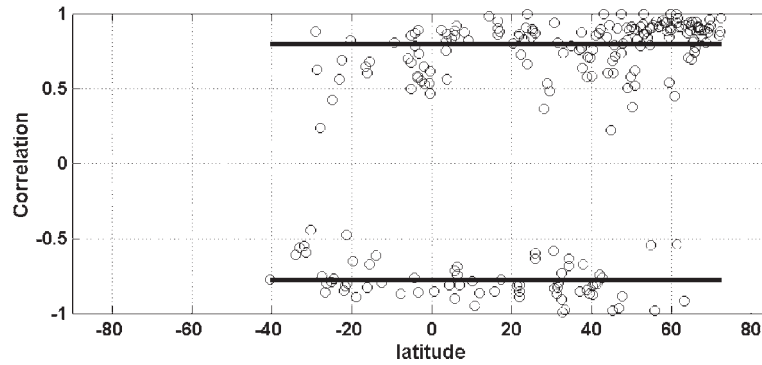


Fig. 2. Statistical validation of the wavelet-reconstruction of annual discharge fluctuations: latitudinal distribution of the correlation coefficient between measured discharges and wavelet reconstructed discharge series. Mean annual correlation coefficients are respectively 0.8 and  $-0.78$  with a maximum of correlation observed at the highest latitudes.

increase of  $1.68 \times 10^{11}$  l/year in [38,39] compared to  $1.84 \times 10^{11}$  l/year in the present contribution) but the second period is characterized by a more rapid increase with an increasing rate multiplied by 3, largely driven by the North American and Asian runoff changes.

At the regional scale, on the first interval (1900–1975), our results are also in accordance with linear regression obtained in [38,39]. Focusing on the 1925–1994 time interval (where most of the global temperature increase occurred) global and continental normalized runoffs ( $R$  in  $10^{16}$  l/year) are characterized by the following trends:

$$\begin{aligned}
 R_{\text{AFRICA}} &\propto 25.79 \times 10^{-5} t \\
 R_{\text{ASIA}} &\propto 152.89 \times 10^{-5} t \\
 R_{\text{EUROPE}} &= 28.98 \times 10^{-5} t \\
 R_{\text{N. AMERICA}} &\propto 204.81 \times 10^{-5} t \\
 R_{\text{S. AMERICA}} &\propto 96.45 \times 10^{-5} t
 \end{aligned} \tag{4}$$

where  $t$  is time in years.

Slight differences between the two reference periods are found for European runoff (stabilisation but still decrease) and South American runoff. African runoff increases rapidly during the first period, and tends to be constant during the second period. The increasing rate of



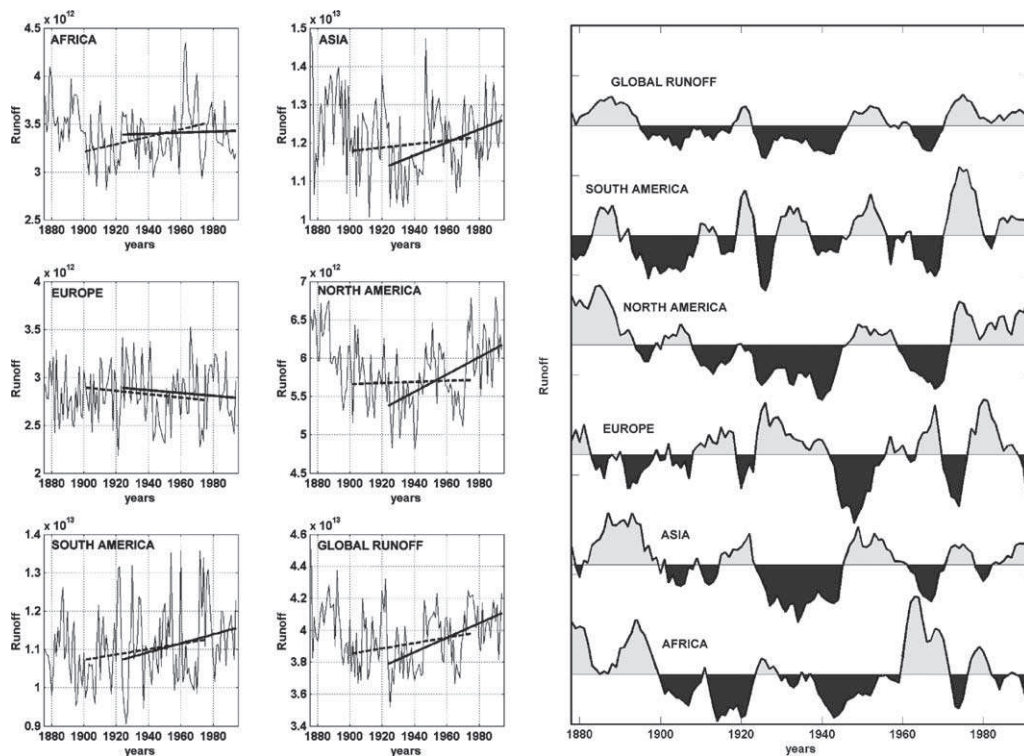


Fig. 3. *Left*: Mean annual runoffs (in  $l/s$ ) for the five continents and linear regressions for 1900–1970 and 1925–1994 intervals. Note that except for the African and European continents, mean annual runoffs increase more rapidly during the second period, itself corresponding to a rapid global warming. (Normalized regression coefficients of runoff fluctuation versus time for the 1900–1970 and 1925–1994 periods are respectively 0.390 and 0.058 for African runoffs, 0.459 and 1.692 for Asian runoff,  $-0.175$  and  $-0.147$  for European runoff, 0.071 and 1.128 for North American runoff, 0.701 and 1.167 for South American runoff, 1.668 and 4.517 for global runoff.) *Right*: 3 year moving average of mean-averaged normalized continental and global runoffs showing the succession of dry (dark gray) and humid (light gray) periods (from bottom to top: Africa, Asia, Europe, North America, South America and Global runoffs). Note the existence of a constant shift or opposition between the different continental runoff fluctuations.

Asian runoff, which greatly contributes to global runoff is multiplied by 3 from the first reference period to the second one. Finally, North American runoff behaviour widely changes from the first to the second period: the relative stability observed during the first period is followed by a rapid increase for the second period.

## 7. Relation between global runoff and temperature

Global temperatures are estimated from a common combination of land air temperature anomalies and sea surface temperature anomalies [19–21]. The runoff-temperature relationship exhibits a global positive correlation. Indeed, the 1875–1925 temperature decrease is correlated with global runoff decrease over the same interval. Then, this tendency is inverted over the second interval (1925–1994). Moreover, a 15 year shift is observed between temperature and runoff response (Fig. 4).

The regression coefficient between temperature and runoff can be expressed in two ways: a simple ratio between temperature and runoff increase versus time or a linear regression between annual mean temperature and runoff. Using an incremental method, the following

relationship holds between runoff and temperature temporal increases:

$$\delta R_{\text{GLOBAL}} = 0.245 \delta T_{\text{GLOBAL}} \quad (5)$$

However, this relationship integrates all the fluctuations of both global temperature and runoff signals, and does not discriminate between yearly fluctuations and the *long-term* trends. Therefore, a linear regression between annual global runoff and annual global temperature was performed for the 1926–1994 period, leading to the following relationship:

$$R_{\text{GLOBAL}} \propto 0.039 T_{\text{GLOBAL}} \quad (6)$$

In order to validate the statistical significance of this slope, a *Student* test is operated. The *Student* test consists in a test of *non-null linear* regression coefficient against null hypothesis. The null hypothesis implies no relationship between variables. The corresponding *t*-statistics is defined as the ratio between slope and standard error on the slope. This *t*-statistic will be large and positive if the slope is significantly greater than zero and large and negative if the slope is significantly less than zero. For example, with 10 degrees of freedom, a *t*-statistic of 8 or greater occurs 0.0006% of time. In the runoff-temperature

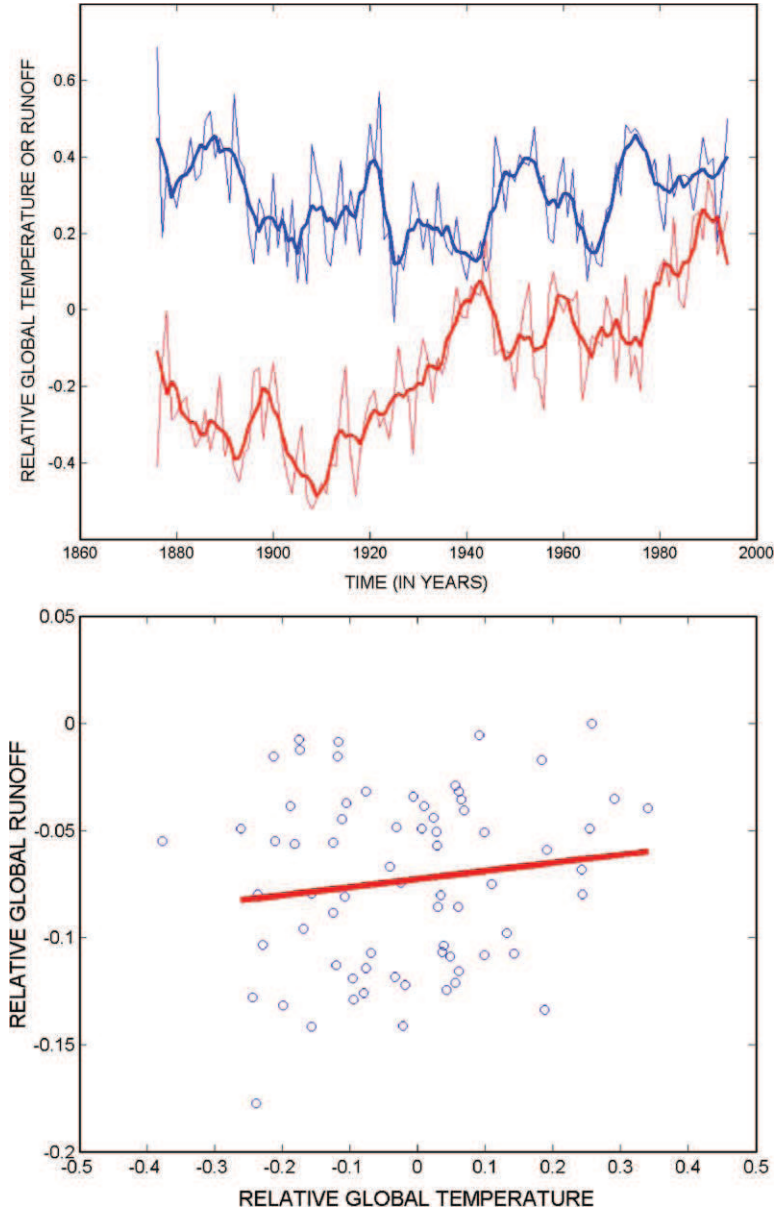


Fig. 4. *Top*: Annual global temperature (red) and global runoff (blue) fluctuations over the 1875–1994 period. Five year moving average of both signals are superimposed in order to highlight the general tendency. Note the existence of both periods: a conjugated decrease of temperature and runoff over the 1875–1910 period followed by a conjugated increase of both signals over the 1925–1994 period. There is a 15 years shift in the global hydrological response to global warmer conditions. *Bottom*: Global temperature versus global runoff relationship over the 1925–1994 period. The linear regression is characterized by a 0.039 slope significantly different from zero ( $T$ -student test equal to 12.45). (For interpretation of the references of colour in this figure legend, the reader is referred to the web version of this article.)

relationship, this slope differs significantly from zero with a  $T$ -student test equal to 12.4. Indeed, the following relationships hold at continental scale:

$$\begin{aligned}
 R_{\text{AFRICA}} &\propto -0.062 T_{\text{NORTH}} \\
 R_{\text{AFRICA}} &\propto -0.059 T_{\text{SOUTH}} \\
 R_{\text{ASIA}} &\propto 0.088 T_{\text{NORTH}} \\
 R_{\text{EUROPE}} &\propto 0.078 T_{\text{NORTH}} \\
 R_{\text{N. AMERICA}} &\propto 0.110 T_{\text{NORTH}} \\
 R_{\text{S. AMERICA}} &\propto 0.057 T_{\text{SOUTH}}
 \end{aligned}
 \tag{7}$$

All slopes differ significantly from zero with *Student* test superior to 10. These correlations might be positive or negative at the continental scale, which indicates the high complexity of the feedback of temperature increase on the hydrological cycle at the regional scale.

## 8. Discussion of results

These hydrological fluctuations accompany an increase of  $\text{CO}_2$  concentrations in the atmosphere. The

investigation of the relationship between runoff and CO<sub>2</sub> or temperature is of high importance for understanding past palaeoclimates of the Earth [6,37] but also for forecasting ongoing changes to the hydrological cycle [1,8].

In paleoclimate models, the amplitude of past atmospheric CO<sub>2</sub> fluctuations is strongly dependent on the ability of global continental silicate weathering (acting as a sink of CO<sub>2</sub>) to counteract changes in the volcanic CO<sub>2</sub> emission. As previously suggested [7,17,44], continental silicate weathering increases when temperature increases, providing the mathematical expression for the negative feedback required to stabilize atmospheric CO<sub>2</sub> (a greenhouse gas) and climate at the geological time-scale (33–35). Global silicate weathering is generally assumed to increase with global runoff, itself assumed to be more efficient under warmer conditions. The relationship between global temperature and global runoff included in the GEOCARB [3–5] model postulates a 3.8% increase in runoff per °C. This relationship is based on the results of rather old simulations performed with climatic models [15,30,31]. In this contribution, we experimentally demonstrate the validity of the runoff-temperature relationship of the GEOCARB model considering a global temperature increase of 0.5 °C.

From a present climate change point of view, the reconstruction of large river discharge allows the estimation of global and continental monthly runoffs fluctuations over the last century, providing a new insight into temporal succession of dry and humid periods. These global hydrological signals also highlight the complexity of the hydrological consequences and feedbacks of recent climate changes but still indicate a rough increase of global runoff over the last 75 years with a 15-year shift. Synchronism or temporal shifts between continents are also put in evidence.

A regression between global temperature and runoff suggests that the global runoff increases by 4% when global temperature rises by 1 °C. This trend is in agreement with recent investigations indicating a global increase of precipitation. However, extrapolation of this runoff-temperature relationship to past and future climate constitutes a non-trivial operation essentially because now the ocean reservoir response to climate warming remains also a matter of debate. From our data, it remains difficult to discriminate anthropogenic effects from natural tendencies in global runoff signals [28,41] even if a recent conjugated acceleration of both global temperature and runoff is observed.

The global runoff increase should be qualified at the continental scale where both increasing (North America, Asia, and South America), stability (Europe) and decreasing (Africa) trends have been shown. These unexpected regional heterogeneities reflect the high nonlinearity of the hydrological cycle response to recent climate change.

In conclusion, this contribution provides the first experimental data-based evidence demonstrating the link between the global warming and the intensification of the global hydrological cycle. This corresponds to more intense evaporation over oceans *coupled* to continental precipitation increase or continental evaporation decrease. This process finally leads to an increase of the global continental runoff.

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