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Temporal Variability of Rain-Induced Floods in Southern Quebec

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1. Introduction

Although the impact of climate warming on streamflow in general and on floods in particular is a much-debated topic (e.g. Koutsoyiannis et al., 2008; Kundzewicz et al., 2008; Räisanen, 2007; Sun et al., 2007), there is general agreement about the geographical variability of these changes. In Quebec, a region characterized by a temperate, continental- and maritime-type climate, a consensus is forming in light of results of climate and hydrological modeling regarding the effects of climate warming on flood magnitude. These effects will depend on the season and the underlying cause of floods. Thus, whereas climate and hydrological models predict a decrease in the magnitude of spring floods resulting from snowmelt (freshets) due to a decrease in the amount of snow falling in winter, they also predict an increase in the magnitude of rain-induced floods as a result of increasing rainfall intensity during summer and fall. Thus, Roy et al. (2001) predicted a significant increase in the intensity of heavy precipitation (20 and 100-year recurrence intervals) which will result in a much greater increase in the magnitude of summer floods. In the Châteauguay River, for instance, peak flow for a flood induced by a 20-year rainfall event will double or triple, depending on initial soil moisture conditions, by the end of the century. However, according to Zhang et al. (2000), no significant increase in rainfall intensity has been observed in Quebec or Canada over the past century, which would explain the absence of any significant change in the interannual variability of the magnitude of rain-induced floods observed in many regions of Canada (Cunderlik & Ouarda, 2009).

While Assani et al. (2011) have shown that the amount of rainfall from August to November has significantly increased in southeastern Quebec, south of parallel 46°N on the South Shore of the St. Lawrence River, no study has looked at the impact of this increase in rainfall on the interannual variability of rain-induced floods. Analysis of the interannual variability of snowmelt-induced spring floods (spring freshets) has revealed no generalized significant decrease in their magnitude (Assani et al., 2010), despite a recorded increase in temperature since the 1970's in Quebec. On the contrary, a significant increase in the magnitude of spring floods on the North Shore of the St. Lawrence is recorded from 1934 to 2000, which is thought to result from the continental nature of climate in this region rather than from increasing temperature. Assani et al. (2010) have also shown that the interannual variability of snowmelt-induced spring floods is significantly correlated with the AMO climate index on the North Shore, and with the SOI and AO climate indices on the South Shore, north and south of parallel 47°N, respectively.

In Quebec, rain-induced floods can sometimes be more devastating than snowmelt-related floods. For instance, in July 1996, the Saguenay-Lac-Saint-Jean area of central Quebec, north of the St. Lawrence River, was the scene of a series of floods which caused more than 1 billion dollars in damage and 10 fatalities. More recently, in the Rivière-au-Renard area of eastern Quebec, south of the St. Lawrence, floods caused several million dollars in damage and two deaths in August 2007. These events led to speculation about the likely increase in the magnitude of rain-induced flood due to climate warming, as predicted by climate and hydrological models. To see whether or not these speculations are supported by observational data, the following two main goals were set for this study:

1. Analyze the interannual variability of the magnitude of rain-induced floods in different regions of Quebec, to see whether this magnitude increased significantly over time, particularly in the southeastern part of the province, south of parallel 46°N on the South Shore of the St. Lawrence River, where the amount of rainfall has increased over time.
2. Determine which climate factors (climate indices) affect the interannual variability of the magnitude of rain-induced floods, in order to see if snowmelt-induced (spring) floods and rain-induced floods are affected by the same climate indices.

2. Methods

2.1 Streamflow data sources and selection of climatic indices

The streamflow data come from Environment Canada's Hydat CD-ROM (2004). Eighteen rivers for which the daily streamflows are measured continuously over a relatively long period wherever possible were selected (table 1 and fig.1). To be able to analyze a greater number of stations, we delimited the study period between 1934 and 2004. Streamflow in these rivers is not affected by the presence of dams. To constitute the seasonal maximum flow series for each year, we selected the highest daily average flow measured in the period from July to October, as this is the period with the highest frequency of rain-induced floods in Quebec.

Several authors have already analyzed the relationship between the climatic indices and streamflows in Québec, Canada and North America. For instance, in Québec, Anctil and Coulibaly (2004) observed a positive correlation between the annual average flows and the PNA (Pacific-North America) and AO indices in the St. Lawrence watershed during the 1938-2000 period. Apart from these two indices, Déry and Wood (2004, 2005) also observed a correlation between streamflows and the PDO (Pacific Decadal Oscillation), the NINO3.4 and SOI (Southern Oscillation index) indices in the other two major Québec watersheds (Hudson Bay and Ungava Bay) during the 1964-2000 period. On the scale of Eastern Canada, a correlation was observed between NAO (North Atlantic Oscillation) and the river flows (see Kingston et al., 2006). On the scale of the North American continent, AMO and PDO are correlated to the annual average flows in many regions of the United States (Enfield et al., 2001; McCabe et al., 2004). Curtis (2008) observed a correlation between AMO and heavy summer rains in the United States and Mexico. At the daily scale, Assani et al. (2010) noted a significant correlation between maximum spring flows and AMO on the North Shore, and AO and ENSO on the South Shore. In this study, we correlated the annual maximum flows to all the climatic indices already correlated to streamflows: AMO, AO, NAO, NINO3.4, PDO and SOI. The data for the AMO, SOI, NINO3.4 and PDO indices are taken from the following websites: http://www.cdc.noaa.gov/ClimateIndices/List. (2007-10-08), and NAO is taken from http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html (2006-10-08), and

AO is taken from http://jisao.washington.edu/data/ao/ (2006-10-08). For each climatic index and for each year, we first derived the seasonal mean of the monthly indices over four months (April-July, May-August, June-September, July-October, and August-November), then over three months (April-June, May-July, June-August, July-September, August-October, and September-November).

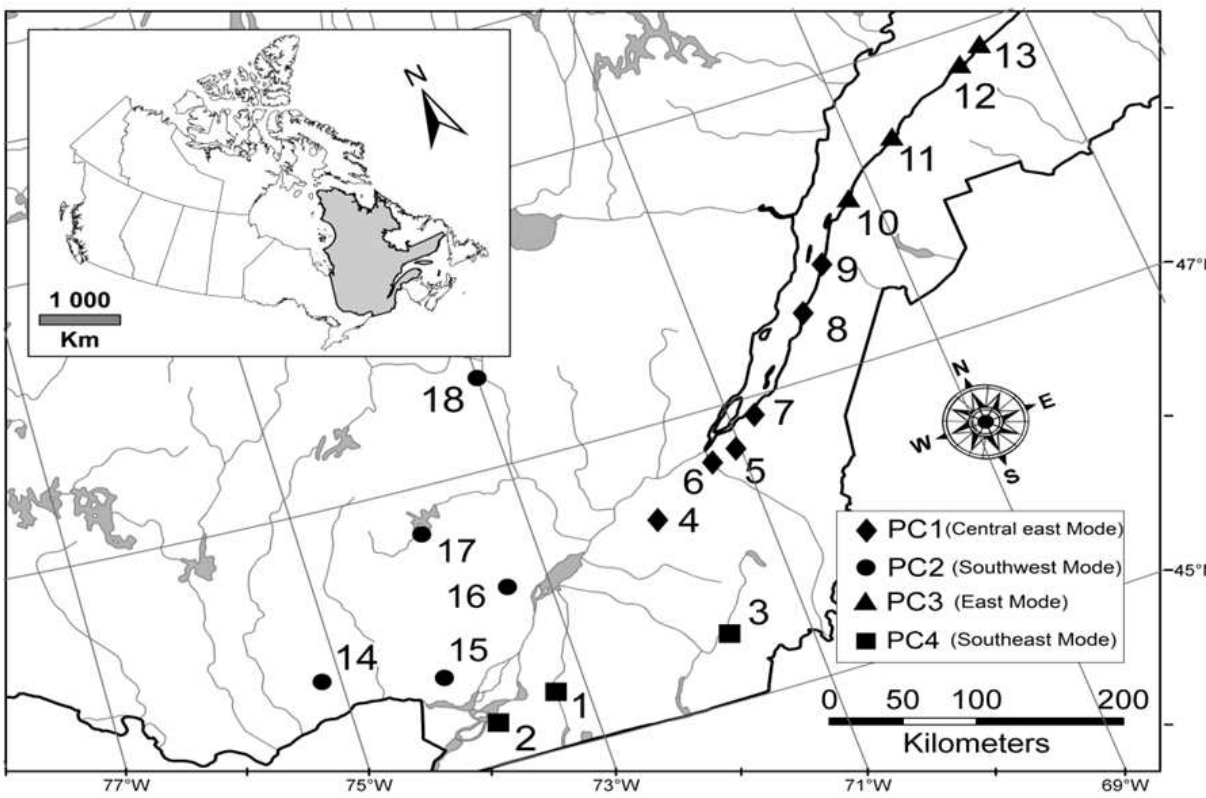

Fig. 1. Location of stations grouped in four modes derived from principal component analysis.

2.2 Statistical data analysis

2.2.1 Interannual variability modes of seasonal daily maximum flows

The first step was to apply principal components analysis (PCA) to the seasonally maximum flow (August to November) data measured at different stations (e.g. Hannachi et al., 2007). We chose this method for comparison with the results of previous work (e.g.Anctil & Coulibaly, 2004; Assani et al., 2010). Moreover, it is widely used in hydroclimatology to analyze the influence of climate factors on the temporal variability of precipitations and streamflows (e.g., McCabe et al., 2004; Vicente-Serrano, 2005). To determine the number of mode patterns (temporal variability modes of annual maximum flow), principal component analysis (mode S) was applied to the correlation matrix (and not to the covariance matrix), based on the correlations calculated between the seasonal flows measured at the different (individual) stations in order to eliminate the influence of extreme values (Bigot et al. 1997), and the effect provoked by a site's local variability (Siew-Yan-Yu et al. 1998). Thus, we analyzed a matrix consisting of 71 lines (number of years of streamflow measurement, from 1934 to 2004) and 18 columns (number of rivers analyzed). We applied the Varimax rotation method to maximize the saturation values of the stations on the principal components and obtain more stable and physically more robust mode patterns.

No	River	Area (km^2)	Latitude (N)	Longitude (W)	MAF (m^3/s)
1	Richelieu	22000	45°18′	73°15′	327
2	Chateaugay	2500	45°17′	73°48′	26.0
3	Eaton	642	45°28′	71°39′	8.6
4	Etchemin	1130	46°38′	71°02′	28.5
5	Nicolet de sud-ouest	544	45°47′	71°58′	8.4
6	Beaurivage	709	46°39′	71°17′	10.5
7	Du Sud	826	46°49′	70°45′	14.7
8	Ouelle	802	47°25′	69°56′	15.6
9	Du Loup	1050	47°49′	69°31′	15.4
10	Trois-Pistoles	932	48°05′	69°11′	13.4
11	Rimouski	1610	48°24′	68°33′	26.5
12	Matane	826	48°46′	67°32′	33.4
13	Blanche	208	48°46′	67°39′	4.8
14	De La Petite Nation	1330	45°47′	75°05′	19.1
15	Du Nord	1170	45°47′	74°00′	21.5
16	L'Assomption	1340	46°00′	73°25′	23.5
17	Matawin	1390	46°41′	73°54′	22.4
18	Vermillon	2670	47°39′	72°57′	37.2

MAF = Mean annual flow

Table 1. Rivers analyzed

The rationale for this maximization is the fact that the criterion used for grouping rivers into modes or homogeneous hydrological regions is based on the values of loadings of rivers on the significant principal components using the "maximum loading" rule. According to this rule, a station is associated with a significant principal component if its loading value on this component is larger than on other components (Vicente-Serrano, 2005). Thus, all stations for which the loadings values are largest on a given principal component define a variability mode or homogeneous hydrological region. However, this loading value must be statistically significant, and since it is not possible rigorously to test a loading value using a statistical test, the correlation between streamflow in each river and the scores of each significant principal component was calculated. This correlation, whose value corresponds to the loading value of the river on a significant component, was thus tested using Student's t test (Assani et al., 2010). A river is therefore correlated to a principal component if its loading value, whose significance has been indirectly tested using the corresponding correlation coefficient, is statistically significant at the 5% level. The Kaiser (1960) criterion based on the eigenvalues of principal components was used to determine the number of significant components, since any principal component with eigenvalue equal to or larger than 1 is considered significant. The grouping of the stations in temporal variability modes was based on "the maximum loading rule". According to this rule, a station is associated with a principal component when the value of its loading is higher on this component than on the others (Vicente-Serrano, 2005).

2.2.2 Analysis of the interannual variability of the magnitude of rain-induced seasonal daily maximum flows

To test the stationarity of the temporal modes, we first applied the regression method (a parametric test) to the scores of the significant principal components (Kundzewicz et al., 2005). However, because it is not possible, using this method, to determine the exact date of a shift in the mean of a hydrologic series, nor whether this shift is abrupt or progressive, the Lombard (1987) method was used to derive these two parameters (date and type of shift).

Suppose we have a series of observations, noted $X_1,...,X_n$, where X_i is the observation taken at time $T = i$. these observations are supposed to be independent. One question of interest is to see whether the mean of this series has changed. If μ_i refers to the theoretical mean of X_i, then a possible pattern for the mean is given by Lombard's smooth-change model, where

$$\mu_i = \begin{cases} \theta_1 & if\ 1 \le i \le T_1; \\ \theta_1 + \dfrac{(i-T_1)\ (\theta_2-\theta_1)}{T_2-T_1}, & if\, T_1 < i \le T_2; \\ \theta_2 & if\, T_2 < i \le n. \end{cases} \tag{1}$$

In other words, the mean changes gradually from θ_1 to θ_2 between times T_1 and T_2. As a special case, one has the usual abrupt-change model when $T_2 = T_1 + 1$.

In order to test formally whether the mean in a series is stable, or rather follows model (1), one can use the statistical procedure introduced by Lombard (1987). To this end, define R_i as the rank of X_i among $X_1,\ldots X_n$. Introduce the Wilcoxon score function $\phi(u) = 2u - 1$ and define the rank score of X_i by

$$Z_i = \frac{1}{\sigma_\phi}\left\{\phi\left(\frac{R_i}{n+1}\right) - \bar{\phi}\right\}, \qquad i \in \{1,...,n\}, \tag{2}$$

where

$$\bar{\phi} = \frac{1}{n}\sum_{i=1}^{n} \phi\left(\frac{i}{n+1}\right) \quad \text{and} \quad \sigma_\phi^2 = \frac{1}{n}\sum_{i=1}^{n}\left\{\phi\frac{i}{n+1} - \bar{\phi}\right\}^2 \tag{3}$$

Lombard's test statistic is

$$S_n = \frac{1}{n^5}\sum_{T_1=1}^{n-1}\ \sum_{T_2=T_1+1}^{n} L_{T_1 T_2}^2, \tag{4}$$

where

$$L_{T_1,T_2} = \sum_{j=T_1+1}^{T_2}\ \sum_{i=1}^{j} Z_i \tag{5}$$

At the 5% level of significance, one concludes that the mean of the series changes significantly according to a pattern of type (1) whenever $S_n > 0.0403$. Note that the test is suitable for the detection of all kinds of patterns in equation (1), including abrupt changes. A complete investigation of the power and robustness of S_n and of five other test statistics proposed by Lombard is given in Quessy *et al*. (2011).

2.2.3 Comparison of the magnitude of rain-induced floods with the magnitude of two- and five-year floods

To determine the extent of a potential change in the magnitude of rain-induced floods, this magnitude was compared with that of annual floods with a 2-year recurrence interval in each watershed. Two-year flood flows were estimated from annual series of measured daily maximum flows for each watershed using the regional approach developed by Anctil et al. (1998). This method is based on the regionalized law of general extreme values (GEV). This estimate was produced follows:

- First, we calculated the quantiles (Q_R) corresponding to the two-year recurrence by means of the formulas developed by Anctil et al. (1998) in the natural homogeneous hydrologic regions. These have been defined in Québec by means of the Hosking and Wallis method. The following equations were used:

$$Q_R = \xi + \frac{(\alpha B)}{\kappa} \tag{6}$$

$$B = 1 - \left\{ -\ln\left[\frac{(T-1)}{T} \right] \right\}^{\kappa} \tag{7}$$

where T is the return period; κ, α and ξ respectively are the shape, location and scale parameters of the standardized parameters of the regional GEV distribution. These parameters are estimated by means of the L-moments method, for which the values were calculated by Anctil et al.(1998) in the natural homogeneous hydrologic regions defined in Québec.

- Finally, we estimated the two-year recurrence quantile (Q_2) downstream from the dams by means of the following equation:

$$Q_2 = Q_R Q_m \tag{8}$$

Q_m is the mean of daily maximum flows for a given river, derived from an annual series compiled from daily flow data measured from October (yr-1) to September of each hydrological year. Using equation 9, it is possible to compare the intensity of the magnitude of rain-induced floods with that of snowmelt-induced floods.

2.2.4 Analysis of the relationship between the annual maximum flow and the climatic indices

The relationship between the seasonal maximum daily flows and the climatic indices was calculated by means of canonical correlation analysis (CANCOR). Compared to other methods of multivariate analysis, CANCOR takes into account both intra-group relationships and the cross correlations between variables of two groups. Indeed, it creates factors (linear transformations of variables, commonly called canonical variables) in the first group (dependent variables) simultaneously to factors in the second group (independent variables). It requires those factors to be orthogonal to each other within the same group, so they are interpreted as independent dimensions of the phenomenon expressed by a group of variables. Thus, the canonical analysis helps to maximize the correlation between the first factor of the first group and the first factor of the second group than between the second factors of the two groups, each one considered orthogonal to the two factors of the first pair, than between the third factors and so on. Each pair of factors expresses a type of relationship between variables in both groups. The intensity of the relationship of a determined type is measured by a canonical correlation coefficient, which is the correlation coefficient between the factors of the same pair. This method allows simultaneous correlation of several dependent variables (streamflows) and several independent variables (climatic indices). It is widely used in climatology (e.g., Chen & Chen, 2003; Dukenloh & Jacobett, 2003; Repelli & Nobre, 2004). The two correlation methods were calculated between the annual climatic indices and the principal components scores (McCabe et al., 2004).

3. Results

3.1 Modes and long-term trend of the variability of rain-induced maximum seasonal flows in Quebec

Using principal component analysis, it was possible to group the 18 rivers into four variability modes each defined by a statistically significant principal component (Fig. 1 and Table 3). The first principal component (East-Central Mode) is correlated with rivers located between 45°30′N and 48°N on the South Shore. The second principal component (Southwest Mode) is correlated with all rivers located on the North Shore. And the last two principal components (East and Southeast Modes) are correlated with rivers on the South Shore located respectively north of 48°N and south of 45°30′N. The total variance explained by the four components exceeds 70%.

The interannual variability of the principal component (PC) scores is shown in Figure 2, and linear regression and Lombard method results are summarized in Tables 3 and 4. Recall that the interannual variability of PC scores reflects the interannual variability of streamflow in rivers with which the principal components are significantly correlated. A statistically significant increase in streamflow is only observed in the Southeast Mode, south of 45°30′N on the South Shore (Figs. 2-3 and Tables 3 and 4). However, analysis of regression results reveals a significant decrease in the interannual variability of the scores of the first principal component, which is correlated with rivers located between 45°30′N and 48°N (East-Central Mode), and a significant increase in the interannual variability of the scores of the second principal component (Southwest Mode). However, the Lombard method could not confirm these changes in principal components I and II (PC I and II). Hence, the above results do not point to any generalized, province-wide increase in the interannual variability of the magnitude of rain-induced daily maximum flows. To determine the extent of the increase observed in the Southeast Mode, the number of times the two-year flood flow calculated from an annual daily maximum flow series was reached or exceeded was determined for the four modes (Table 5). The two-year flood flow was reached or exceeded in 50% of the watersheds, and analysis of its geographical distribution reveals that the two-year flood magnitude is attained more frequently on the South Shore south of 48°N (reached or exceeded in 7 out of 8 watersheds) than elsewhere.

N°	Rivers	PCI	PCII	PCIII	PCIV
Southeast Mode					
1	Richelieu	0.040	0.145	0.055	**0.848**
2	Chateaugay	0.074	0.202	0.116	**0.848**
3	Eaton	0.420	0.202	0.070	**0.533**
East-Central Mode					
4	Etchemin	**0.876**	0.170	0.108	-0.089
5	Nicolet de sud-ouest	**0.766**	0.162	-0.156	0.386
6	Beaurivage	**0.721**	0.175	0.210	0.067
7	Du Sud	**0.652**	0.081	0.235	0.127
8	Ouelle	**0.689**	0.098	0.389	-0.001
9	Du Loup	**0.710**	0.112	0.509	0.015
East Mode					
10	Trois-Pistoles	0.377	0.068	**0.818**	-0.073
11	Rimouski	0.310	0.240	**0.814**	0.025
12	Matane	0.132	0.218	**0.727**	0.157
13	Blanche	0.031	0.092	**0.753**	0.108
Southwest Mode					
14	De La Petite Nation	0.023	**0.829**	0.140	0.317
15	Du Nord	0.320	**0.816**	0.053	0.133
16	L'Assomption	0.262	**0.804**	0.172	0.152
17	Matawin	0.082	**0.890**	0.166	0.180
18	Vermillon	0.092	**0.772**	0.145	-0.041
Explained variance (%)		22.2	20.7	17.2	11.8

The higher values of Rivers loadings on PCs show in the bold.

Table 2. Principal components Loadings of Rivers

PC (Mode)	a	b	R^2	Fc
PC I (East-Central Mode)	-0.013	25.28	0.070	**5.194**
PC II (Southwest Mode)	0.011	22.19	0.0541	**3.946**
PC III (East Mode)	0.007	13.29	0.0194	1.365
PCIV (Southeast Mode)	0.019	36.63	0.148	**11.986**

a = slope of the curve; b = y-intercept; R^2 = coefficient of determination; Fc = value of the Fisher-Snedecor test statistic. Fc values which are statistically significant at the 95% level are shown in bold.

Table 3. Regression parameters for curves fitted to the factorial scores of the principal components

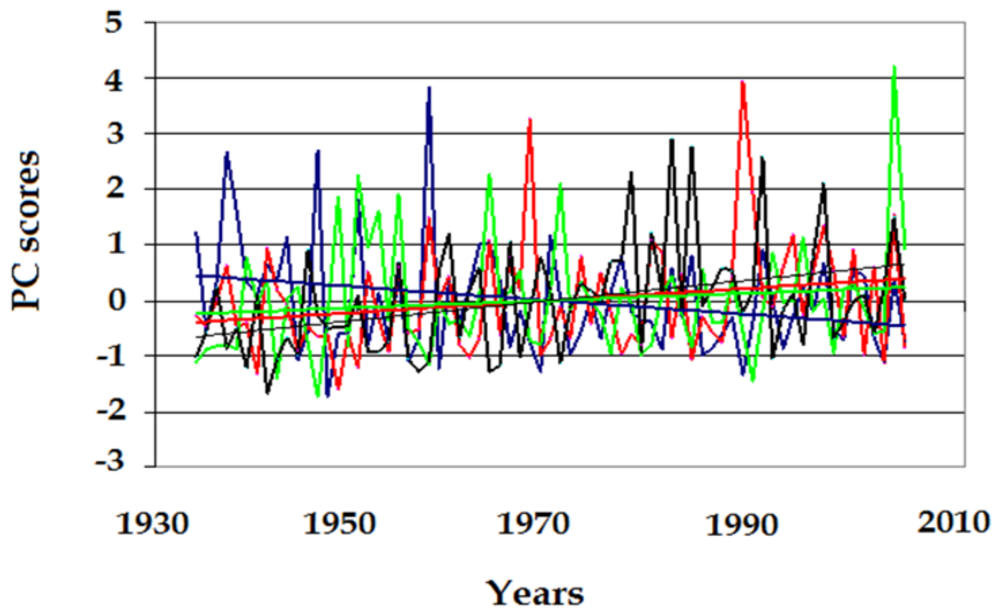

Fig. 2. Interannual variability of the Principal components scores (1934-2004). PCI = East-Central Mode (blue curve); PCII = Southwest Mode (red curve); PCIII = East Mode (red curve); PCIV = Southeast Mode (black curve);

Principal Components (Mode)	Sn	Year of change
PC I (East-Central)	0.0257	-
PC II (Southwest)	0.0281	-
PC III (East)	0.0132	-
PC IV (Southeast)	0.1152	1958

The value of Sn > 0.043, shown in bold, is statistically significant at the 95% level.

Table 4. Analysis of the interannual variability of PC scores (1934-2004). Lombard test results.

3.2 Relationship between climate indices and streamflow (PC scores)

Results of the canonical analysis of correlations are shown in Table 6. Each of the principal components, which represent the variability of streamflow in the four modes, is correlated with a canonical variable. This reflects the fact that the principal components are independent from one another, the first one being correlated with V3, the second, with V2, the third, with V4 and the last, with V1. As for climate indices, only quarterly indices derived from the means of the September to November indices show a significant correlation with principal components. The AMO index is correlated with the canonical variable W1. Since the V1 and W1 canonical variables are correlated, AMO is correlated with the last principal component, which represents streamflow variability (PC scores) in the Southeast Mode. This correlation is negative. AO is positively correlated with the second principal component (PC II), which encompasses rivers on the North Shore (Southwest Mode). The SOI climate index is correlated with the third principal component (PC III) linked to rivers located north of 48°N. Finally, the first principal component is not significantly correlated with any climate index. As for explained variance, it is larger for canonical variables correlated with principal components than for those correlated with climate indices.

No	River	Qmax	Q2-year (m^3/s)	Fr
Southeast Mode				
1	Richelieu	896	865	0
2	Châteauguay	418	403	3
3	Eaton	183	177	2
Center-east Mode				
4	Etchemin	253	244	2
5	Nicolet	142	137	2
6	Beaurivage	179	173	0
7	Du Sud	246	237	1
8	Ouelle	119	112	3
9	Du Loup	170	160	0
East Mode				
10	Trois-Pistoles	212	200	0
11	Rimouski	268	252	0
12	Matane	377	355	1
13	Blanche	41	38	4
Southwest Mode				
14	De La Petite Nation	82	79	0
15	Du Nord	191	184	0
16	L'Assomption	155	150	2
17	Matawin	142	137	0
18	Vermillon	224	216	0

Qmax = mean of annual daily maximum flows (October (yr-1) to September) calculated for the 1934-2004 interval; Q2 = two-year flood flow estimated from the annual series using the regional method; Fr= number of times Q2 was reached or exceeded from August to October during the 1934-2004 interval.

Table 5. Number of times (Fr) the two-year annual flood flow (estimated using the regional method) was reached or exceeded in the various watersheds, from 1934 to 2004.

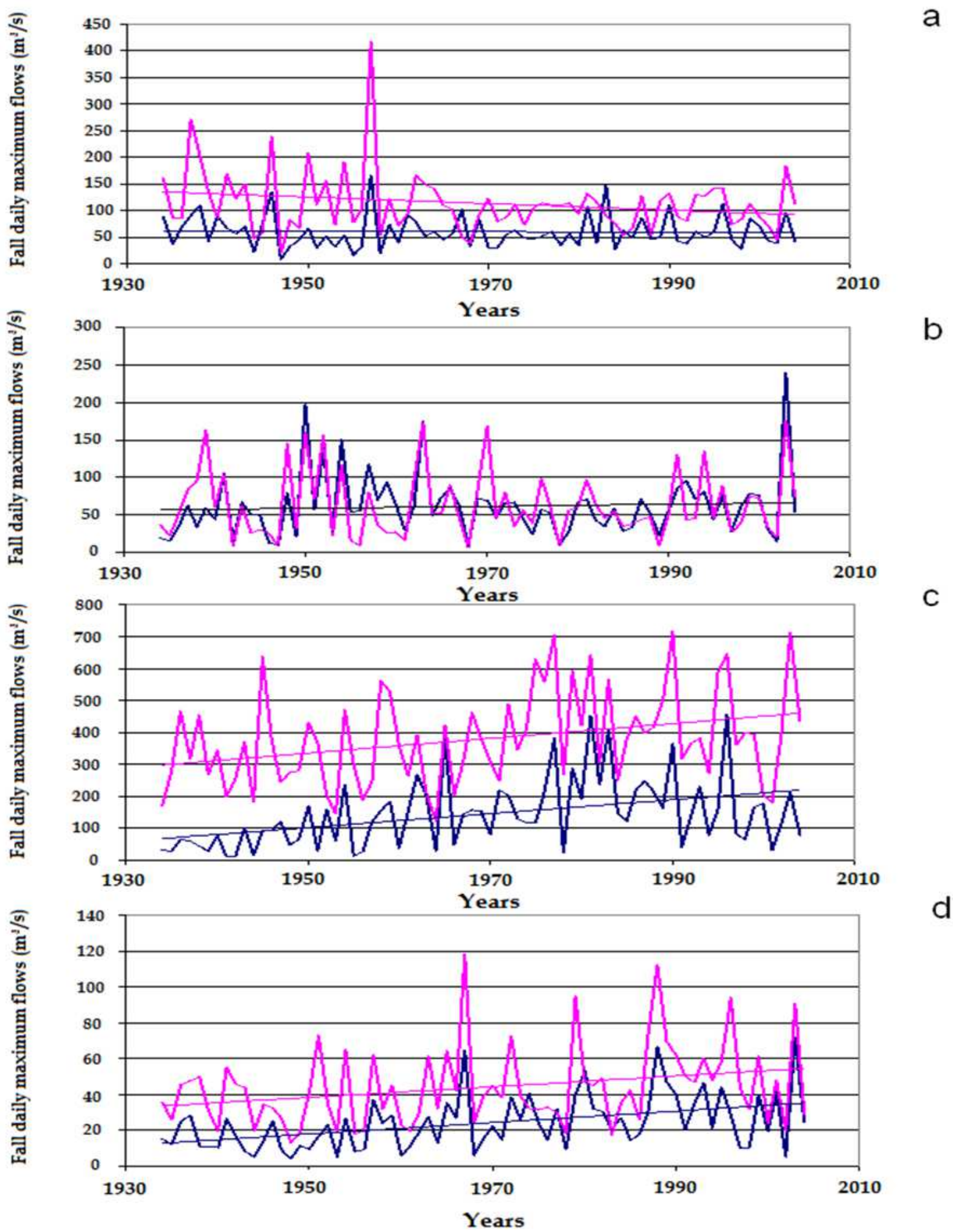

Fig. 3. Interannual variability of the fall daily maximum flow of a few river. a = Nicolet Sw (blue curve) and Etchemin (red curve) rivers in Center-East Mode; Rimouski (blue curve) and Trois-Pistoles (red curve) Rivers in East Mode; Châteaugay (blue curve) and Richelieu (red curve) Rivers in Southeast Mode; De la Petite Nation (blue curve) and Matawin (red curve) Rivers in Southwest Mode

Variables	V1	V2	V3	V4	W1	W2	W3	W4
PC I	-0.127	0.440	**0.862**	0.286				
PC II	0.528	**0.840**	-0.314	-0.054				
PC III	-0.371	0.142	-0.410	**0.821**				
PC IV	**0.873**	-0.408	0.160	0.291				
AMOfall					**-0.864**	0.388	0.435	-0.236
AOfall					0.316	**0.832**	-0.363	0.369
NAOfall					-0.249	0.197	0.032	0.187
PDOfall					0.477	0.035	0.429	-0.599
SOIfall					-0.028	-0.195	0.328	**0.884**
EV (%)	29.9	27.0	25.9	20.4	22.7	18.4	12.3	26.0

EV = explained variance. The higher values of coefficient of correlation show in bold.

Table 6. Correlation between the principal components and canonical variables (V), and correlation between climatic indices and canonical variables (W).

4. Discussion and conclusion

In light of the interannual variability of snowmelt-induced floods (Assani et al., 2010), analysis of the interannual variability of rain-induced floods in Quebec during the period from 1934 to 2004 led to four significant results:

(i) The 18 rivers analyzed were grouped into four modes: one on the North Shore and three on the South Shore, the latter being located south of 45°30′N, between 45°30′N and 48°N, and north of 48°N, respectively. For spring snowmelt-induced floods, the same rivers defined three modes: one on the North Shore and the other two on the South Shore, on either side of parallel 47°N. The effect of local factors on the origin of floods could account for the presence of an extra mode for rain-induced floods. Thus, rain-induced floods may be caused by three factors: summer storms resulting from convective motion (convective rainfall), polar front-induced rainfall (frontal rainfall), and rainfall caused by other tropical cyclones in the Atlantic basin. Local factors have a stronger effect on convective rainfall than on the other two types of rainfall. However, because the necessary data were not available, the effect of each of the above three factors on flood genesis in Quebec could not be quantified. In springtime, floods are almost exclusively caused by snowmelt. As such, the effect of local factors on snowmelt-induced flood is limited.

(ii) Analysis of the interannual variability of streamflow only revealed a significant increase in the southeast, south of 45°30′N on the South Shore (Southeast Mode). Two factors may account for this increase:

- An increase in agricultural surface area, as this is a region of Quebec in which agricultural lands make up more than 20% of all watersheds. This high proportion of farmland could lead to significant runoff which, in turn, would result in an increase in flood magnitude over time. However, since Muma et al. (2011) showed that in increase in agricultural surface area in a watershed has no impact on the magnitude of rain-induced flood flows in Quebec, this factor cannot account for the increase in magnitude of flows observed over time in the region.

- An increase in precipitation. Analysis of the interannual variability of seasonal precipitation from August to November revealed a significant increase in the amount of rainfall south of parallel 46°N from 1950 to 2000 on the South Shore, as shown in Figure 3 for a number of stations in the Richelieu and Châteauguay watersheds. This increase is thought to be the main cause of the increase in rain-induced flows observed in that part of the province, and could also account for the higher frequency of attainment and/or exceedance of the two-year annual flood magnitude in the Southeast Mode than in the other three modes.

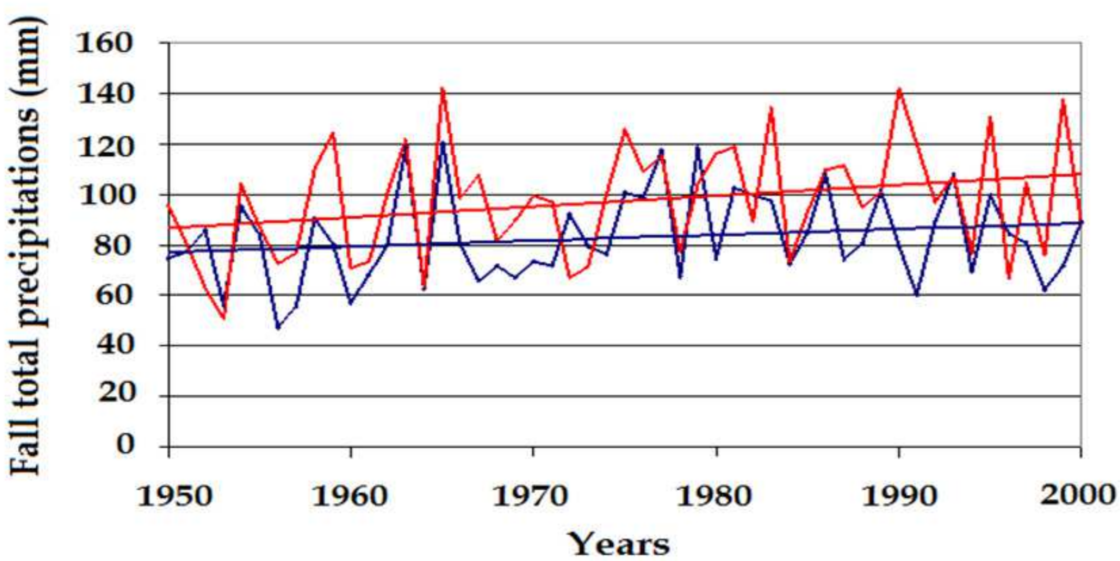

Fig. 5. Interannual variability of August to November precipitation over the period from 1950 to 2000 at two stations in the Châteauguay and Richelieu rivers watersheds, south of 45°30′N. Les Cèdres station: blue curve; Magog station : red curve

(iii) Analysis of the relationship between rain-induced flood flows and climate indices revealed a correlation between the interannual variability of flood flows and climate indices in three modes. In the Southeast Mode, located south of 45°30′N and characterized by a significant increase in streamflow and precipitation, flood flows show a negative correlation with the AMO index; in the Southwest Mode, flows are positively correlated with the AO index; and in the East-Central Mode, flows are negatively correlated with AO. For snowmelt-induced spring flows, AMO is negatively correlated with streamflow in North Shore rivers (Southwest Mode), this mode being characterized by a significant increase in spring flood flows over the 1930-2000 interval. AO is negatively correlated with streamflow in South Shore rivers located south of 47°N (Southeast and East-Central Modes) and SOI is positively correlated with streamflow in rivers located north of 47°N (Assani et al., 2010). This comparison leads to the conclusion that rain- and snowmelt-induced floods are not correlated with the same climate indices in the Southeast and Southwest Modes. However, it also shows that AMO is correlated with rain-induced (Southeast Mode) and snowmelt-induced (Southeast Mode) floods characterized by a significant increase in flow over time in Quebec.
The effect of these three indices (AMO, AO, and SOI), which show a significant correlation with streamflow in the three modes, on the interannual variability of streamflow in Quebec

has been described by Assani et al. (2010). AMO is correlated negatively to precipitation and streamflow in many regions of North America (e.g. Curtis, 2008; Enfield et al., 2001; McCabe et al., 2004). In fact, positive values of the index (positive phase) coincide with a decrease in precipitation and streamflow in many regions of North America in general, and in Quebec in particular, whereas negative values (negative phase) of the index are associated with an increase in precipitation and streamflow. During a positive AMO phase, more frequent changes in the circulation and shear of the westerly and a weakening of cyclonic activities and transfer of water vapour from the Atlantic Ocean to the continent are observed. These factors trigger a decrease in precipitation and streamflow in Quebec. As for AO, it is positively correlated with rain-induced flood flows in Quebec. According to the scheme proposed by Kingston et al. (2006), when AO is in positive phase (high values), an increase in SSTs (surface ocean temperatures) is observed (more northerly Gulf Stream position), along with a reduced influence of the East Coast trough. As a result, the frequency of southerly airflow increases, and storm tracks coincide with the coast more often. Thus, streamflow increase in Québec. Finally, the influence of ENSO would lead to an increase in atmospheric humidity and cyclonic activities in the region during El Niño episodes. These two factors are responsible for an increase in summer and winter precipitation in Québec.

This study shows that, in the region characterized by a significant increase in rainfall, the magnitude of flood flows has significant increased. Moreover, the frequency of flows larger than the two-year annual flood flow has also increased in the watersheds. These findings confirm climate model predictions about the impact of climate warming on the intensity of rain-induced floods in Quebec. However, this increase is not a generalized, province-wide phenomenon.

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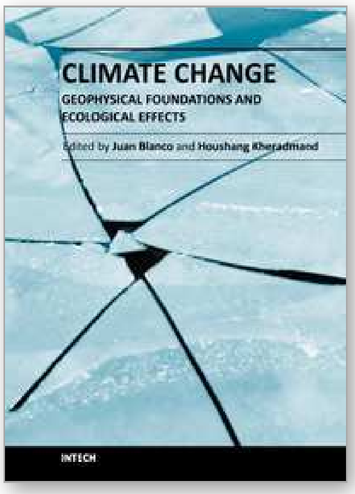

Climate Change - Geophysical Foundations and Ecological Effects
Edited by Dr Juan Blanco

ISBN 978-953-307-419-1
Hard cover, 520 pages
Publisher InTech
Published online 12, September, 2011
Published in print edition September, 2011

This book offers an interdisciplinary view of the biophysical issues related to climate change. Climate change is a phenomenon by which the long-term averages of weather events (i.e. temperature, precipitation, wind speed, etc.) that define the climate of a region are not constant but change over time. There have been a series of past periods of climatic change, registered in historical or paleoecological records. In the first section of this book, a series of state-of-the-art research projects explore the biophysical causes for climate change and the techniques currently being used and developed for its detection in several regions of the world. The second section of the book explores the effects that have been reported already on the flora and fauna in different ecosystems around the globe. Among them, the ecosystems and landscapes in arctic and alpine regions are expected to be among the most affected by the change in climate, as they will suffer the more intense changes. The final section of this book explores in detail those issues.

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