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Temporal variability of the magnitude and timing of winter maximum daily flows in southern Quebec (Canada)

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SUMMARY

The temporal variability of winter climate in southern Quebec is characterized by increasing temperature and rainfall, but decreasing snowfall. The goal of the study was to analyze the impact of these changes on the magnitude and timing of winter maximum daily flows. Hydrologic series for seventeen tributaries of the St. Lawrence River were analyzed over the period from 1934 to 2010. The most noteworthy result, obtained using the Lombard method, was to highlight a nearly generalized shift in mean values of the series in the early 1970s. This shift reflects a significant increase in the magnitude of winter maximum daily flows after that decade, interpreted to result primarily from snowmelt, which is increasingly frequent at the end of winter. The frequency of the dates of occurrence of winter maximum daily flows increased significantly during the last winter decade (ten days) after the 1970s for most rivers in southern Quebec. The copula method did not, however, reveal any significant change in the dependency between the timing and magnitude of winter maximum daily flows over time. Finally, canonical correlation analysis revealed that the magnitude of winter maximum daily flows is positively correlated with the Pacific Decadal Oscillation (PDO), while their dates of occurrence are correlated with the North Atlantic Oscillation (NAO).

1. Introduction

Given the storage of precipitation as snow, winter is characterized by generally low flows in Quebec (e.g. Assani et al., 2012; Assani and Tardif, 2005). However, because air temperatures are increasing, winter precipitation as rain is more frequent and the amount of winter snow is decreasing (e.g., Ionita et al., 2014; Surfleet and Tullos, 2013). In addition, snowmelt is occurring earlier (Madsen et al., 2014; Morán-Tejeda et al., 2014) and more frequently in winter than in spring. According to most climate models, increasing rainfall frequency should lead to an increased frequency and intensity (magnitude) of winter flooding as a result of higher runoff on slopes (Boyer et al., 2010a,b; Sczypta et al., 2015). According to Verhaar et al. (2010, 2011), the strongest floods will occur more often in winter than in spring. Morphologically, one of the main expected impacts of this increase in winter flows is enhanced bank erosion processes and sediment transport in some tributaries of the St. Lawrence River in Quebec (Boyer et al., 2010a,b; Verhaar et al., 2010, 2011). From an ecological standpoint, aside from higher water temperatures, the increase in winter flows should significantly impact the life cycle of certain aquatic organisms. For instance, the survival rate of juvenile Atlantic salmon (*Salmo salar*) in streams is primarily influenced by winter flows, which determine the available habitat volume (Cunjak et al., 1998). Consequently, given the current climate warming trend, analyzing the changes that affect winter flood regimes in continental temperate regions is of the utmost importance considering the impact of these changes on aquatic organisms in fluvial ecosystems.

In Quebec, studies examining the interannual variability of natural streamflow in winter are restricted to analyses of monthly or seasonal low or mean flows (e.g. Assani et al., 2011a,b, 2012; Assani and Tardif, 2005; Zhang et al., 2001). To date, no study has looked at winter maximum daily flows. However, in a recent study, Assani et al. (2014) showed that winter maximum daily water levels in the St. Lawrence River have decreased significantly since the 1980s, a fact they attribute to the decreasing amount of snow highlighted by Brown (2010) in spite of increasing temperatures observed in Quebec since the 1970s (Yagouti et al., 2008). Finally, in a recent study, Guerfi et al. (2015) observed a significant decrease in the amount of snow in winter at many stations in the

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St. Lawrence River watershed in Quebec. This decrease occurred during the 1980s, coinciding with diminishing water levels in the St. Lawrence. The results of these studies raise the following fundamental question: are winter maximum daily flows decreasing over time in the St. Lawrence River watershed, like winter water levels in the river itself?

In addition, the climate index that most heavily influences the spatial and temporal variability of winter temperature and precipitation (snow and rain) in Quebec is still open to some debate. Some authors believe that the El Niño/Southern Oscillation (ENSO) is the main variability factor (e.g., Shabbar, 2006), while others attribute it to the North Atlantic/Arctic Oscillation (NAO/AO), (e.g., Kingston et al., 2006; Qian et al., 2008), the Atlantic Multidecadal Oscillation (AMO) (Assani et al., 2014), or the Pacific Decadal Oscillation (PDO) (Brown, 2010). It is important to establish which of these climate indices affects the spatial and temporal variability of these characteristics (timing and magnitude) of winter maximum daily flows in Quebec. From a hydroclimatic standpoint, it should be recalled, southern Quebec has been subdivided into three homogeneous hydroclimatic regions: the eastern region, located on the South Shore of the St. Lawrence River north of 47°N, characterized by a maritime climate; the southwest region, located on the North Shore, characterized by a continental climate; and the southeast region, located on the South Shore south of 47°N, characterized by a mixed climate (e.g., Assani et al., 2010, 2011a,b). Guerfi et al. (2015) showed that the decrease in the amount of snow was greater in the southwest than in the other two regions located on the South Shore.

Consequently, the three goals of the study are as follows:

1. To compare the interannual variability of the magnitude of maximum daily flows in the three hydroclimatic regions of southern Quebec, the underlying hypothesis being to test whether decreasing amounts of snow resulted in a decrease in maximum daily flows in winter in southern Quebec (Brown, 2010; Guerfi et al., 2015). This decrease is greater on the North Shore (southwest region) than on the South Shore (Guerfi et al., 2015).
2. To compare the interannual variability of the dates on which these winter maximum daily flows occur in the three hydroclimatic regions of Quebec to determine whether the increased frequency of precipitation as rain has affected these dates in southern Quebec.
3. To establish which large-scale climate indices correlate significantly with the magnitude and timing of winter maximum daily flows in Quebec.

2. Methods

2.1. Station location and sources of flow data

As already mentioned, southern Quebec is subdivided into three hydroclimatic regions (Fig. 1). At least five hydrologic stations were selected in each of these three regions based on (1) the existence of flow data measured over a relatively long period and (2) the absence of dams or other human activity that might have significantly modified the natural hydrologic regime of the rivers. Characteristic features of the selected stations are shown in Table 1 and their location is shown in Fig. 1. Winter in Quebec generally extends from December to March.

Daily flow data measured during the period from 1934 to 2010 were taken from the Environment Canada website (http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm, viewed in March 2012) and climate data were taken from the National Oceanic and Atmospheric Administration (NOAA) website (http://www.cdc.noaa.gov/ClimateIndices/List, viewed in June 2013). As part of the study, we selected five climate indices shown to affect the spatial and temporal variability of hydroclimatic variables in North America in general, and in Quebec in particular (e.g., Anctil and Coulibaly, 2004; Assani et al., 2010, 2011a,b, 2012; Mazouz et al., 2012, 2013). These climate indices are the following: AMO (Atlantic Multi-decadal Oscillation), AO (Arctic Oscillation), NAO (North Atlantic Oscillation), PDO (Pacific Decadal Oscillation), and SOI (Southern Oscillation Index). Climate indices for the AMO and PDO were taken from the following website: http://www.cdc.noaa.gov/ClimateIndices/List (viewed on 10-06-2013), the NAO from http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html (viewed on 10-06-2008), the AO from http://jisao.washington.edu/data/ao/ (viewed on 10-02-2007), and the SOI from http://www.cgd.ucar.edu./cas/catalog/climind/soi.html (viewed on 10-02-2007). Data for these climate indices (NAO, AO and SOI) after 2006 were taken from the NOAA website: http://www.esrl.noaa.gov/psd/data/climateindices/list/. For each index, an annual mean was derived using monthly values from January to December. Data for all these indices since 1950 are available on the NOAA website: http://www.esrl.noaa.gov/psd/data/climateindices/list/. Annual means were calculated over the period from 1934 to 2010.

For more than 70% of the analyzed watersheds, data on air temperature, snow-water equivalent and rainfall amount were unavailable. In addition, where such data were available, they were either non-existent or incomplete prior to 1950 for almost every watershed and even after 1950, for some watersheds. Accordingly, these three climate variables were not correlated with the two characteristics (magnitude and timing) of winter maximum daily flows.

2.2. Statistical analysis

2.2.1. Hydroclimatic series

Two streamflow data series were produced for each river: a series of winter maximum daily flows and a series of dates on which these flows occurred. The first series comprises the largest daily flow value measured from December to March (the four months considered to be winter months in southern Quebec) for each year from 1934 to 2010. This period allowed an analysis of the largest number of rivers over a relatively long time period (more than 70 years of flow measurements). The second series comprised the maximum daily flow occurrence dates. These occurrence dates were first converted to Julian days, starting on July 1 and ending on June 30 of the following year (year + 1), to avoid a sharp break in date values from December 31 to January 1. Then, the frequencies per decade (10-day intervals) from December to March of the dates of occurrence of maximum daily flows were calculated for each river over the period from 1934 to 2010. Moreover, we excluded the February 29 during leap years in order to compare all years based on the same number of winter days. Thus, the winter season was divided into 12 decades, the first comprising the first 10 days of December, and the last, the last 10 days of March. This winter season breakdown into decades was the only breakdown that highlighted changes in the occurrence dates maximum daily flows over time. Other breakdown approaches and methods cited in the literature (e.g., Burn, 2008; Cayan et al., 2001; Cunderlik and Ouarda, 2009; Déry et al., 2009; Hodgkins et al., 2003; Hodgkins and Dudley, 2006; Magillan and Graber, 1996) did not yield conclusive results. To determine the temporal change in the frequency of winter maximum daily flows for each decade, we compared the frequencies of these flows before and after 1970 using the Chi-square method. As we show later, the change in magnitude of maximum daily flows occurred after that year for most of the analyzed rivers.

As far as climate indices are concerned, four data series were produced for each index: two series of mean values were