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Inter-annual to inter-decadal streamflow variability in Quebec and Ontario in relation to dominant large-scale climate indices

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SUMMARY

The impacts of large-scale climate oscillations on hydrological systems and their variability have been documented in different parts of the world. Since hydroclimatic data are known to exhibit non-stationary characteristics, spectral analyses such as wavelet transforms are very useful in extracting time–frequency information from such data. As Canadian studies, particularly those of regions east of the Prairies, using wavelet transform-based methods to draw links between relevant climate indices [*e.g.*, the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO)] and streamflow variability are not common, this study aims to analyze such relationships for the southern regions of Quebec and Ontario. Monthly and annual streamflow data with a record length of 55 years were used to capture streamflow variability at intra-annual, inter-annual and inter-decadal scales. The continuous wavelet transform spectra of monthly streamflow data revealed consistent significant 6- and 12-month periodicities, which are likely associated with strong seasonality factors. Its annual counterparts showed four different significant periodicities: up to 4 years, 4–6 years, 6–8 years, and greater than 8 years – all of which occurred after the late 1960s/early 1970s. Wavelet coherence analyses show that the influence of ENSO and NAO at the inter-annual scale occurs at 2–6 year periodicities, and the influence of PDO occur at periodicities up to 8 years and exceeding 16 years. Correlations between these climate indices and streamflow were computed to determine the time delay of streamflow response to the influence of ENSO, NAO, and PDO. The lag times ranged from 6–48 months (for monthly data) and 1–4 years (for annual data). This research contributes to our understanding of streamflow variability over the southern parts of Quebec and Ontario, and the role of ENSO, NAO, and PDO phenomena on this variability. These relationships can be also used to improve hydrological forecasting and water resources management in Ontario and Quebec.

1. Introduction

Detecting the presence of important periodicities and trends in hydrological variables (e.g. precipitation, streamflow and groundwater), which are associated with large-scale climate indices is important in examining the influence of these indices on hydrological systems (Pasquini and Depetris, 2007). Among the most prevalent climate indices affecting the North American climate are the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO) (Enfield and Mestas-Nuñez, 1999; Anctil and Coulibaly, 2004; Coulibaly and Burn, 2004; Hanson et al., 2004; Massei et al., 2011). For example, Gobena and Gan (2006) indicated that long-term flow forecasting in southwestern Canada is influenced more strongly by ENSO and PDO indices than the Pacific North American (PNA) index. Positive PDO phases were found to be correlated to dry periods in areas from the Pacific Northwest to the Great Lakes and the Ohio Valley, as well as to warmer winters and spring seasons in northwestern North America (Mantua and Hare, 2002; Perez-Valdivia et al., 2012). Brown and Goodison (1996) reported that there were significant correlations between the NAO and December snow-cover in southern Quebec and Ontario between 1915 and 1992. The influence of ENSO and NAO was found to be regional and varied at the inter-annual scale (Ropelewski and Halpert, 1986; Gobena and Gan, 2009; Ouachani et al., 2011; Fu et al., 2012). The influence

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of PDO on the other hand, appears to occur at longer time scales such as inter-decadal to multi-decadal scales (Perez-Valdivia et al., 2012; Ouyang et al., 2014) because a PDO phase (positive or negative) may last for about 2–3 decades or more (Mantua and Hare, 2002; MacDonald and Case, 2005). For example, the influence of PDO on groundwater level variability in the Canadian Prairies is apparent at 18–22 year time scales (Perez-Valdivia et al., 2012).

It is well known that hydro-climatic time series exhibit non-stationary properties and may contain trend, periodic and autoregressive components, as well as random residual factors (Kite, 1993; Coulibaly and Baldwin, 2005; Adamowski et al., 2010, 2012; Campisi et al., 2012; Tiwari and Adamowski, 2014; Pingale et al., 2014; Araghi et al., 2015). Recently, spectral analysis-based wavelet transform (WT) techniques have shown promise in analyzing and exploring the non-stationary characteristics of hydro-climatic variables (e.g. Anctil and Coulibaly, 2004; Mwale et al., 2009; Massei et al., 2011; Fu et al., 2012; Haidary et al., 2013; Rathinasamy et al., 2013; Belayneh et al., 2014; Nourani et al., 2014; Rathinasamy et al., 2015). Wavelet transform proves to be particularly useful in localizing important features of a non-stationary signal, at their exact temporal location, as well as identifying the relative contributions of signal components which may vary with time (Drago and Boxall, 2002). Having mentioned the advantages of WT, and although WT has been used in a variety of fields, its applications in hydro-climatic studies are relatively recent (Labat, 2005; Fu et al., 2012). Using continuous wavelet transform (CWT) to analyze streamflow variability in the Mississippi River Basin between 1934 and 2008, Massei et al. (2011) showed the CWT spectra's capacity to identify three prominent streamflow discontinuities in 1950–1960, 1970, and 1985. Similarly, Anctil and Coulibaly (2004) also used the CWT to identify a temporal point of inflection (*i.e.*, c. 1970) in the inter-annual variability of streamflow measured at 18 stations in southern Quebec, Canada. Using a similar CWT approach, Coulibaly and Burn (2004) identified two temporal points of inflection in the variability of annual Canadian streamflow (*i.e.*, c. 1950 and c. 1970) at 2–3-year and 3–6-year time scales.

Based on CWT, wavelet coherence (WTC) and cross wavelet transform (XWT) each can be used to calculate the correlation between two variables and thus, to identify the influence of large-scale climate indices on hydrological variables. A XWT spectrum between two signals shows regions where there are common high power between the signals, whereas a WTC spectrum shows regions where the signals covary, without necessarily exhibiting high power (Grinsted et al., 2004). For example, Ouachani et al. (2011) applied CWT, XWT and WTC to examine the influence of several large-scale climate indices (ENSO, NAO, PDO, Mediterranean Oscillation, Western Mediterranean Oscillation) on precipitation and streamflow variability in the Medjerda Basin in Tunisia. It was found that the climate indices affected the basin's precipitation variability, which subsequently affected its streamflow variability (Ouachani et al., 2011). Using XWT and WTC, Keener et al. (2010) analyzed the relationships between the sea surface temperature (SST) anomaly in Niño region 3.4 and precipitation, streamflow, and nitrate concentrations ([NO_3^-]) in Georgia's Little River watershed. Even though both XWT and WTC methods showed consistent ENSO influence at 3–7 year time scales, significant regions in the XWT spectrum (between SST and [NO_3^-] data) were mostly due to the much stronger SST signature in the streamflow. The WTC results showed an appearance of significant periodicities in the spectra of SST-precipitation and SST-streamflow, but an absence of significant periodicities in the spectrum of SST-[NO_3^-]. The WTC results support the interpretation that the strong signature of SST in streamflow (which are also affected by precipitation) may have caused the appearance of significant regions in the XWT spectrum of SST-[NO_3^-] (Keener et al., 2010). Comparing the results of XWT and WTC analyses, Maraun and Kurths (2004), Labat (2010), and more recently, Fu et al. (2012) have also concluded that, WTC is more useful than XWT in analyzing the linkages between two hydro-climatic variables, because significant regions observed in a XWT spectrum may over represent the variability in one variable, and therefore may not reflect an actual relevant cause-and-effect relationship (Fu et al., 2012). In light of these findings, the present study used the WTC approach in examining the influence of a climate index on streamflow variability.

In Canada, a number of studies have used wavelet-transform based approaches to analyze the relationship between two hydro-climatic time series (*e.g.*, Anctil and Coulibaly, 2004; Coulibaly and Burn, 2004, 2005; Gan et al., 2007; Gobena and Gan, 2009; Mwale et al., 2009; Fu et al., 2012; Perez-Valdivia et al., 2012). Using the CWT, Anctil and Coulibaly (2004) analyzed the variability of streamflow in Quebec after dividing the study area into time-longitude categories (*e.g.*, east–west regions for 2–3, 3–6, and 6–12-year time scales), and found that each was linearly correlated to several large-scale climate indices. The most intense streamflow variability that occurred in the 2–3 year time scales was mostly affected by PNA and Northern Hemisphere Annular Mode (NAM), particularly after 1970. For the 3–6-year wavebands, important streamflow variability after 1970 was more strongly affected by PNA, NAO, and ENSO (Anctil and Coulibaly, 2004). Similarly, when analyzing the annual streamflow variability from 79 Reference Hydrometric Basin Network (RHBN) stations across Canada, Coulibaly and Burn (2004) noted intense variability in the 2–3 and 3–6-year time scales, with 1970 also serving as one of the inflection points. After 1970, PNA and NAO indices were found to affect the streamflow activity in the 2–3-year time scales, while NAO and ENSO indices explained most of the streamflow variability in the 3–6 year time scales (Coulibaly and Burn, 2004). Fu et al. (2012) advocated the use of CWT and WTC in analyzing the influence of solar activity and ENSO on streamflow variability in southern Canada. They found that solar activity and ENSO affected streamflow variability at 2–7, 11, and 22 year time scales, and the combined influence of both solar activity and ENSO was apparent in 18–32 year time scales (Fu et al., 2012). These studies have demonstrated the useful applications of CWT and WTC in extracting and localizing important information in non-stationary hydro-climatic time series, as well as in studying the relationships between large-scale climate indices and hydrological variables.

In Canada, most of the studies that used WT based approaches (including CWT and WTC) to analyze the influence of climate indices on hydrological variables were conducted for the western or southwestern regions of the country (*e.g.* Gan et al., 2007; Gobena and Gan, 2009; Mwale et al., 2009; Fu et al., 2012). Though the strongly regional influence of these large-scale climate indices is well recognized, few similar studies have been conducted for regions east of the Canadian Prairies. In light of this, the present study sought to explore the use of CWT and WTC methods to study the influence of ENSO, NAO, and PDO indices on streamflow variability in southern Quebec and Ontario. More specifically, this study: (i) uses the CWT approach to reveal the temporal characteristics of streamflow, ENSO, NAO, and PDO data, (ii) uses the WTC approach to analyze the linkages between streamflow and ENSO, NAO, and PDO variability, and (iii) determines the time lag of streamflow response to the influence of ENSO, NAO, and PDO. To the authors' knowledge, the present study represents the first use of CWT and WTC, in the context of southern Quebec and Ontario watersheds, to specifically explore the relationships between streamflow variability and ENSO, NAO, and PDO indices, as well as to determine the time lag for streamflow to respond to