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Spatial and temporal variability of Canadian seasonal precipitation (1900–2000)

Paulin Coulibaly *

Department of Civil Engineering and School of Geography & Earth Sciences, McMaster University, Hamilton, ON, Canada L8S 4L7

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Abstract

Wavelet and cross-wavelet analysis are used to identify and describe spatial and temporal variability in Canadian seasonal precipitation, and to gain further insights into the dynamical relationship between the seasonal precipitation and the dominant modes of climate variability in the Northern Hemisphere. Results from applying continuous wavelet transform to seasonal precipitation series from 201 stations selected from Environment Canada Meteorological Network reveal striking climate-related features before and after the 1940s. The span of available observations, 1900–2000, allows for depicting variance and covariance for periods up to 12 years. Scale-averaged wavelet power spectra are used to simultaneously assess the temporal and spatial variability in each set of 201 seasonal precipitation time series. The most striking feature, in the 2–3-year period and in the 3–6-year period—the 6–12-year period is dominated by white noise and is not considered further—is a net distinction between the timing and intensity of the temporal variability in autumn, winter and spring–summer precipitation. It is found that the autumn season exhibits the most intense activity (or variance) in both the 2–3 year and the 3–6 year periods. The winter season corresponds to the least intense activity for the 2–3 year period, but it exhibits more activity than the spring–summer for the 3–6 year period.

Cross-wavelet analysis is provided between the seasonal precipitation and four selected climatic indices: the Pacific North America (PNA), the North Atlantic Oscillation (NAO), the Northern Hemisphere Annular Mode (NAM) originally called the Arctic Oscillation, and the sea surface temperature series over the Niño-3 region (ENSO). The wavelet cross-spectra revealed coherent space–time variability of the climate–precipitation relationship throughout Canada. It is shown that strong climate/precipitation activity (or covariance) in the 2–6 year period starts after 1940 whatever the climatic index and the season. Prior to year 1940, only local and weaker 2–6 year activity is revealed in western Canada essentially in winter and autumn, but overall a non-significant precipitation/climate relationship is observed prior to 1940. Correlation analysis in the 2–6 year band between the seasonal precipitation and the selected climatic indices revealed strong positive correlations with the ENSO, the NAO, and the NAM in eastern and western Canada for the post-1940 period. For the period prior to 1940, the correlation tend be negative for all the indices whatever the region. A particular feature in the correlation analysis results is the consistently stronger and positive NAM–precipitation correlations in all the regions since 1940. The cross-wavelet spectra and the correlation analysis in the 2–6 year band suggest the presence of a change point around 1940 in Canadian seasonal precipitation—that is found to be more likely related to NAM dynamics.

Keywords: Seasonal precipitation; Space–time variability; Wavelet analysis; Climatic patterns; Change point

1. Introduction

Large-scale patterns of atmospheric circulation determine the distributions of surface temperature and precipitation over land surface, which in turn control key components (e.g. streamflows, soil moisture, evaporation) of the hydrologic cycle. Hence, the identification and understanding of coherent and recurrent climatic patterns along with their connections to the temporal and spatial variability of precipitation can be particularly relevant to the interpretation of variations and long-range persistence

* Tel.: +1 905 525 9140; fax: +1 905 546 0463.
E-mail address: couliba@mcmaster.ca

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within hydrological records. Furthermore, a better understanding of the temporal and regional connections between low-frequency climatic fluctuations and the variations of seasonal precipitation can lead to better hydrologic system modeling (e.g. improved long-range streamflows or reservoir inflows forecast), and hence improved water resources planning and management. Such information is also essential to our ability to better assess climate change impact on water resources systems at regional scale. However, assessing the changes in atmospheric patterns and their relationships to the variability of precipitation remains a difficult task owing to their complex and nonlinear nature. In previous attempts to investigate how much regional variability in surface temperature and rainfall can be accounted for by the low-frequency climatic variability modes (or indices), different statistical methods such linear regression and empirical orthogonal functions have been used (see [49,34]). However, both statistical methods suffer severe limitations as the relationships between the low-frequency climatic modes and the hydro-climatic variables (e.g. precipitation, streamflows) are nonlinear. As an alternative to the linear regression methods, recent studies have resorted to non-parametric multitaper method of spectral analysis (e.g. see [32,41])—a more direct measure of the occurrence process. However, all these approaches assume stationary time series, but continuous wavelet analysis have revealed that the interannual variability of phenomena such as El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) are non-stationary processes, since their variance changes in frequency and intensity through time (e.g. see [45,14,6]). More importantly, in order to gain insight into the finer temporal structures of seasonal precipitation—which is essential to the understanding of the complex hydrology–climate relationship, a decomposition of precipitation time series into time–frequency space is required to identify the dominant modes of variability and to determine how these modes vary in time. This has been done by resorting mostly to Fourier transform [13,24,27]. A major limitation of the Fourier analysis is that it does not retain the location of a particular event in time and space, nor does it perform well on irregularly spaced events or non-stationary signals [38]. Standard short-term Fourier transform is particularly limited by its window of fixed arbitrary length. It has been recently shown that temporal structures of rainfall–runoff records cannot be taken into account adequately using classical spectral or correlation analyses [26]. As an alternative, wavelet transforms have been proposed. A major property of the wavelet transform is its ability to provide a robust approach to decompose and represent time series into a finer scale-time domain without a window with arbitrary limited length. Furthermore, it can permit distinguishing between two signals which have very similar Fourier spectra.

Wavelet analysis has been used in geophysics and meteorology to identify coherent convective storm structures and characterize their temporal variability (e.g. see [22,40,39] or to analyze localized variations within geophysical time series including climatic indices (e.g. [37,15,25,28]). In hydrology, wavelet analysis has been recently applied to examine daily rainfall–runoff relationships in a karstic watershed [26], and also to characterize daily streamflow in the United States [38], and to describe reservoir inflow variability in northern Quebec [6]. More recently, wavelet analysis has been used to describe variability in Canadian streamflows [7,8]. No study has fully investigated low-frequency space–time variability of Canadian seasonal precipitation records and their nonlinear relationships with dominant climatic patterns in the Northern Hemisphere. This analysis aims to fill this gap, and enhances our understating of the seasonal climate–hydrology variability which is essential to our ability to improve long-range hydrologic forecast in this region.

In this analysis, continuous wavelet transforms are used to allow a finer analysis of the time-varying structures of the seasonal precipitation records and the precipitation–climate relationships throughout Canada. The main objectives of this analysis are to describe and document the seasonal variability in Canadian precipitation using wavelet and cross-wavelet analysis. This study also aims to examine the role of the dominant climatic patterns in the Northern Hemisphere on the seasonal variability of Canadian precipitation during the last ten decades (1900–2000). Furthermore, the analysis aims to provide additional information for a better understanding and interpretation of the striking features recently revealed in Canadian seasonal streamflows [8]. The remainder of the paper is organized as follows. A description of the study area and the datasets are first provided. The continuous wavelet and cross-wavelet analysis method is presented next. Results from the wavelet and cross-wavelet analysis are then reported, and finally some conclusions are drawn.

2. Study area and datasets

2.1. Precipitation time series

Daily total precipitation records are gathered from the rain gauges of Environment Canada meteorological network. A total of 201 stations (see Fig. 1) are selected based on record length to minimize the limited data record problem and allow longer period (up to decadal time scale) analysis. The selected stations cover all the reference hydrometric basins in Canada (see [7,8]), however there are a limited number of stations representing the Canadian north, and there are few longer-term stations from central Ontario, Manitoba, and Quebec. As such, the selected datasets consist only of the best available precipitation time series with longer record lengths. The meteorological variable selected for this research is the seasonal total precipitation given that the study is mainly concerned with the complex seasonal variability inherent to Nordic climate precipitation. Owing to the large size of the study area (Fig. 1), the length of season is region dependent. Here