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Effects of persistence and large-scale climate anomalies on trends and change points in extreme precipitation of Canada

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ABSTRACT

Slowly varying (trend) and abrupt (change points) changes in annual maximum daily precipitation (AMP) and seasonal maximum daily precipitation (SMP) across Canada for 223 stations in six regions during four periods (1900–2010, 1930–2010, 1950–2010 and 1970–2010) were analyzed. Variants of the Mann-Kendall (MK) test considering influences of short-term persistence (STP), long-term persistence (LTP) and large-scale climate anomalies on trend detection were applied to detect trends, and the Pettitt test was used to evaluate change points. The results indicate that there was a mix of increasing and decreasing trends for Canadian AMPs and SMPs. Most regions in Pacific Maritime, central Boreal regions and the Atlantic Maritime showed an increase in AMP, while a decrease in Canadian Prairies and most Boreal regions. More stations showing statistically significant increases than decreases in spring, summer and autumn SMPs were found while there was a statistically significant decrease (increase) in winter SMP over southern (northern) Canada. LTP significantly increased the likelihood of trends detected in AMPs and SMPs. The effects of STP on the trend detection were also evident as shown by the differences in results obtained from the MK tests with and without considering the effect of STP. The effects of large-scale climate anomalies on trends were significant for winter SMPs. More than 1/4 of stations were detected with statistically significant change points in AMPs and SMPs which occurred around 1960–1990. More stations showed significant change points than trends, and winter showed more evident trends and change points in SMPs than other three seasons. Trends and change points detected were field-significant.

1. Introduction

Impacts of climate variability and human activities can result in gradual (trend) or abrupt (shift) changes in the hydrologic cycle. A changing hydroclimate could result in under- or over-designed civil engineering projects (Forsee and Ahmad, 2011; Jakob, 2013). Thus, in view of recently observed changes in the magnitude and frequency of hydroclimatic variables, the fundamental assumption of stationarity for traditional hydroclimatic frequency analysis may no long hold (Milly et al., 2008, 2015). Nonstationary analysis of hydroclimatic processes under anthropogenic climate change has been criticized because of additional uncertainties associated with nonstationary models (Montanari and Koutsoyiannis, 2014; Serinaldi and Kilsby, 2015). However, because of large sampling error in analyzing time series with long-term persistence (LTP), a stationary process could be mistaken to be nonstationary (Koutsoyiannis and Montanari, 2015; Montanari and Koutsoyiannis, 2014). In this study, we focus on detecting both slowly varying (trend) and abrupt (change points) changes in Canadian extreme precipitation, and the possible effects of persistence in the time series on precipitation trends.

A stationary time series has a time-invariant probability distribution function which means that it does not exhibit trends or change points (Brillinger, 2001; Koutsoyiannis, 2006). For Canada, several studies have examined the stationarity of annual or seasonal total precipitation time series by trend analysis and they found an increase in the annual total precipitation mostly due to an increase in the number of small to moderate precipitation events (Mekis and Vincent, 2011; Vincent and Mekis, 2006; Zhang et al., 2001, 2000), while statistically significant increase (decrease) in snowfall has been mainly detected in northern (southwestern) Canada (Mekis and Vincent, 2011; Vincent and Mekis, 2006). In contrast, past studies in trend analysis of observed

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heavy or extreme precipitation over Canada show inconsistent results, with no statistically significant trend (Kunkel, 2003; Kunkel and Andsager, 1999; Zhang et al., 2001) and a statistically significant increasing trend (Alexander et al., 2006; Burn and Taleghani, 2013; Peterson et al., 2008; Vincent and Mekis, 2006) detected in either the frequency or the intensity of extreme precipitation, possibly because of different data sets and techniques used in these studies. However, all these studies detected precipitation variability ranging from interannual to interdecadal time scales. In contrast, climate change scenarios of some global climate models downscaled by regional climate models mostly project a more intense and frequent daily and multi-day precipitation events for most Canadian regions (Mailhot et al., 2010; Mladjic et al., 2011). There is a need to do a comprehensive investigation on changes to historical extreme precipitation of Canada.

However, there have been limited studies on the change points in the probability distribution of precipitation, especially on extreme precipitation, such as Fu et al. (2015) who analyzed change points of precipitation over western Canada, although a shift could have significant impacts on the regime of extreme precipitation, as Villarini et al. (2009, 2011, 2013) found in the continental US. Therefore, we investigated both trends and change points in the time series of annual maximum daily precipitation (AMP) and seasonal maximum daily precipitation (SMP) of Canada.

Moreover, recent trend analysis of extreme and heavy Canadian precipitation (e.g., Vincent and Mekis, 2006; Zhang et al., 2001, 2000) did not consider the possible influence of large-scale climate anomalies, even though extreme and heavy precipitation could be linked to large-scale climate anomalies over North America (Tan et al., 2016; Raible, 2007; Yin and Branstator, 2008; Yiou and Nogaj, 2004; Zhang et al., 2010). St. Jacques et al. (2010, 2014) found that trends in streamflow of watersheds in Northern Rocky Mountain and Canadian Prairie Provinces are partly due to the ~60-year cycle of the Pacific Decadal Oscillation (PDO).

In the trend analysis of station precipitation data, the serial and inter-station correlations between stations of a regional domain are usually overlooked even though correlations between station streamflow data were widely considered in the trend analysis of Canadian streamflow data (e.g., Burn and Elnur, 2002; Ehsanzadeh and Adamowski, 2010; Khaliq et al., 2009a,b; Khaliq and Gachon, 2010; Yue et al., 2003, 2002). However, the trends of Canadian extreme precipitation were estimated with the serial correlation, inter-station correlation and impacts of large-scale climate anomalies removed.

Hydroclimatic variables tend to exhibit temporal persistence in extremes such as floods and droughts. Short-term persistence (STP) are usually accounted for by an autoregressive-1 model (Sagarika et al., 2014; Yue et al., 2003), while LTP, first detected by Hurst (1951), can significantly influence trends estimated from conventional tests involving the independent assumption, such as the Mann-Kendall (MK) test (Cohn and Lins, 2005; Kendall, 1975). The MK test tends to over-estimate the significance of trends of data with LTP (Cohn and Lins, 2005; Franzke, 2010, 2012; Koutsoyiannis, 2006; Koutsoyiannis and Montanari, 2007; Sagarika et al., 2014). The LTP of a hydroclimatic series is usually related to large-scale climate anomalies of interannual and/or interdecadal scales (Klemeš, 1974; Potter, 1976). The consideration of LTP can better explain certain nonstationary behaviors such as temporal trends in a time series (Koutsoyiannis, 2006; Koutsoyiannis and Montanari, 2007; Potter, 1976).

On the other hand, the presence of cross-correlation in a regional dataset could cause an over-estimation of the actual number of trends. Thus, it could distort the outcome of certain statistical tests (Lettenmaier et al., 1994; Livezey and Chen, 1983). Therefore, in this study, we used five variants of the MK tests to evaluate the effect of STP, LTP and large-scale climate anomalies on the trend identification of Canadian AMP and SMP, and then the field-significance of each regional trend test was estimated. In addition, possible change points of Canadian AMP and SMP time series were also estimated using the nonparametric, Pettitt test (Pettitt, 1979) to further investigate their nonstationary characteristics. All trends and change points estimated were tested for their field-significance using the Walker test and the false discovery rate (FDR) method (Wilks, 2006).

The paper is organized as follows: Section 2 gives an overview of precipitation data used and large-scale climate anomalies in terms of climate indices; Section 3 describes the research methodology; Section 4 discusses the results and finally Section 5 the summary and conclusions.

2. Data

2.1. Precipitation

Given Canada is the second largest country in the world, its climate varies widely from the north (west) to south (east), and so to analyze changes to extreme Canadian precipitation can be challenging and has to be done on a regional basis. In this study, on the basis of geographical areas and Canadian ecozones classified by Environment Canada (1996), we divided Canada into six primary ecoregions (Fig. 1), which are Arctic Maritime, Atlantic Maritime, Boreal Regions, Pacific Maritime, Canadian Prairies and Taiga Regions. Then trends, change points and their field-significance were analyzed region by region.

Daily precipitation data used in this study were taken from the second generation adjusted historical Canadian climate data (AHCCD) database, which has 463-station of daily precipitation data statistically adjusted for known measurement issues, especially for snow data (Mekis and Vincent, 2011). This is the most homogeneous, long-term observed daily precipitation data currently available for Canada, and recently updated to 2012. The length of station daily precipitation data ranges from 27 to 172 years, with an average of 84 years. Generally, precipitation measurements began in northern Canada (above 60°N) in the 1950s, which was much later than in southern Canada in the early 1900s. Therefore, stations with short precipitation measurements tend to be located in northern Canada. Details of this dataset are given in Mekis and Vincent (2011). To investigate long-term changes in extreme precipitation, we analyzed precipitation data of AHCCD using four different periods to assess uncertainties associated with trends and change points estimated with respect to the length of a historical record. These four periods selected are (Fig. 1): (1) 1900–2010 (111 years for 41 stations), (2) 1930–2010 (81 years for 140 stations), (3) 1950–2010 (61 years for 201 stations) and (4) 1970–2010 (41 years for 223 stations). These four periods were also adopted to analyze the changes in the frequency of extreme precipitation across Canada (Tan and Gan, 2016). AMP and SMP time series of spring (March-May), summer (June-August), autumn (September-November) and winter (December-February) were extracted from daily time series for each station studied.

2.2. Large-scale climate anomalies

We selected four large-scale climate indices that have been linked to precipitation variability of Canada (e.g., Gan et al., 2007; Tan et al., 2016; Shabbar et al., 1997) or to North America (Ropelewski and Halpert, 1986; Zhang et al., 2010): (1) Southern Oscillation Index (SOI), which is the normalized monthly differences in sea level pressure (SLP) between Tahiti and Darwin (Ropelewski and Jones, 1987; Kevin E. Trenberth, 1984) that