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Detection of Linkages Between Extreme Flow Measures and Climate Indices

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Abstract**—**Large scale climate signals and their teleconnections can influence hydro-meteorological variables on a local scale. Several extreme flow and timing measures, including high flow and low flow measures, from 62 hydrometric stations in Canada are investigated to detect possible linkages with several large scale climate indices. The streamflow data used in this study are derived from the Canadian Reference Hydrometric Basin Network and are characterized by relatively pristine and stable land-use conditions with a minimum of 40 years of record. A composite analysis approach was used to identify linkages between extreme flow and timing measures and climate indices. The approach involves determining the 10 highest and 10 lowest values of various climate indices from the data record. Extreme flow and timing measures for each station were examined for the years associated with the 10 largest values and the years associated with the 10 smallest values. In each case, a re-sampling approach was applied to determine if the 10 values of extreme flow measures differed significantly from the series mean. Results indicate that several stations are impacted by the large scale climate indices considered in this study. The results allow the determination of any relationship between stations that exhibit a statistically significant trend and stations for which the extreme measures exhibit a linkage with the climate indices.

Keywords**—**flood analysis; low-flow events; climate change; trend analysis; Canada.

I. Introduction

POTENTIAL impacts of climate change can alter the risk to critical infrastructure resulting from changes to the frequency and magnitude of extreme events. Operational decisions for water resources infrastructure are dependent on both the timing and magnitude of flows, and therefore climate change impact assessment must consider both these characteristics. Traditionally, water resource systems have been designed on the assumption that the available flow records for a location reflect stationary climatic conditions. In view of the recent climate change, the assumption of stationarity in the flow records cannot be justified. Consequently, past flow records cannot be directly used to quantify design risks associated with the occurrence of extreme events, both high flow and low flow, in the future. Design of hydrological systems is, therefore, likely to be more reliable if the factors causing changes in extreme events are considered.

A better understanding of the nature of hydrologic variability due to climate changes is needed to advance the ability to predict extreme flows. Large scale climate indices are considered as an important source of inter-annual variability in weather and climate. Large scale climate indices such as El-Niño Southern Oscillation Index (ENSO) and Pacific Decadal Oscillation (PDO) capture the anomalous states of sea surface temperature (SST) and surface atmospheric pressure. The persistence of these climate signals and their teleconnections to land surface hydrologic response can provide valuable indicators of impacts on streamflows on a local scale.

Studies have been carried out to investigate linkages between climate indices and precipitation [14]. Both daily precipitation amounts and precipitation frequencies have been found to be affected by ENSO events [51], [20]. To consider an integral view of potential climate change, streamflow rather than precipitation and temperature records are analysed for linkages with climate indices. Streamflow series have the advantage over pure precipitation series that the complex variability of precipitation, evapo-transpiration, vegetation cover, topography and other physical characteristics of the region are reflected in the streamflow records. Analysis of streamflow records is likely to lend credibility to recent climate change modelling efforts, and would help detect climate change impacts on the hydrological regime. It is therefore of interest to investigate the impacts of large scale climate indices on extreme flow measures such as the magnitude and timings of high flows and low flows.

This paper investigates four extreme flow measures: 1. High flow magnitude (HFM); 2. High flow timings (HFT); 3. Low flow magnitude (LFM); and 4. Low flow timings (LFT) for possible linkages with large scale climate indices. Trends in extreme hydrological events, both high and low flow events, for a set of streamflow gauging stations in Canada have been analyzed. The database of Canadian rivers investigated here has been constructed to represent a diversity of hydrological conditions encompassing different flood generating processes and reflects a national scale analysis of trends. The principal objective of the research presented herein is to detect any statistically significant linkages that exist between extreme flow and timing measures and climate indices. This objective is achieved through conducting a trend

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analysis of four extreme flow measures: HFM, HFT, LFM, and LFT for several Canadian rivers. Those stations that show relationship with climate indices and also show trend for each of the four extreme flow measures have been identified. The intent behind the research presented herein is to advance the understanding of the linkages that exist behind large scale climate indices and extreme flow measures.

II. Literature Review

Several studies have examined trends and patterns in measures of the timing of runoff for a catchment. Changes in the date of occurrence of the spring snowmelt peak streamflow have been investigated [3], [49]. The onset of spring runoff has been estimated by defining a pulse day [10]. In [54], and [5], the date of the onset of spring runoff was defined using an automated approach based on current and previous streamflow values. In [54], [27], [28], the centre of volume date was used to define the timing of runoff. Three measures have been used to examine changes in streamflow timing in snowmelt dominated watersheds in western North America [47].

Extensive studies have been carried out in various regions of the world to investigate trends in hydro-meteorological variables with a view to detect impacts of climate change. The time series of annual runoff volumes and annual as well as seasonal flood peaks in Sweden has been analyzed [36]. In [44], streamflow records from 36 gauging stations in five major river basins of Minnesota, USA for trend and correlations using Mann-Kendall test and moving averages method were examined. An overview of discharge trends and flow dynamics of South American rivers draining the southern Atlantic seaboard has been presented [2]. The temporal trends of annual and seasonal precipitation and temperature in the Hanjiang basin in China have been analyzed using Mann-Kendall and linear regression techniques [30]. The trends in water levels and streamflow in Yangtze river basin in China have also been investigated [55].

Numerous studies have been undertaken in Canadian basins to assess climate change impacts on hydro-meteorological variables. The Mann-Kendall test was applied to identify trends in hydrological variables [4]. In [1], the trends and variability in the hydrological regime for the Mackenzie Basin in northern Canada was analyzed. Analysis was conducted on hydrological data from a network of 54 hydrometric stations and meteorological data from a network of 10 stations using Mann-Kendall test. Winter month flows exhibited strong increasing trends and an earlier onset of the spring freshet was noted over the basin. The temperature, precipitation and streamflow data for sites in British Columbia and the Yukon was examined [50]. The trends in annual streamflow volume in northern British Columbia and the Yukon have been investigated [17]. The trends in streamflow data in the Liard and Athabasca River Basins in northern Canada have been examined [5], [6]. In [12] and [13], a decreasing trend in streamflow in the Canadian Arctic was detected and attributed to various large scale atmospheric phenomenon. Several studies have also been carried out to examine trends and patterns in measures of the timing of runoff for a catchment.

III. Climate Indices

Connections between the timing measures and various climate indices were explored to determine if linkages exist. Six climate indices were examined in this context. The El Niño-Southern Oscillation (ENSO) is one of the best known climate signals for which teleconnections have been found with a variety of hydrological variables including precipitation [32], [42] and streamflow [9]. The ENSO is an important source of inter-annual variability in weather and climate with a periodicity of 2–7 years. The Niño 3.4 index is used herein to represent the ENSO and captures Pacific sea surface temperature (SST) anomalies between latitudes 50 S and 50 N and longitudes 1700 W and 1200W. The use of the ENSO as a primary variable in streamflow forecasting using statistical methods has been evaluated [19]. A method has been devised to incorporate the ENSO in streamflow forecasting for the Columbia River [21].

The Pacific Decadal Oscillation (PDO) is a pattern of Pacific climate variability that shifts phases on at least inter-decadal time scale, usually about 20 to 30 years [40]. The PDO has been shown to have strong connections with hydrological variables, particularly in the Pacific Northwest [21], [43]. For parts of North America, warm phases are generally associated with warmer and drier winters while cool phases are associated with cooler and wetter winters. PDO has been shown to be a predictor for Columbia River streamflow [22]. The PDO state in water supply forecasts to produce significant value for water management has been incorporated in [22].

The Arctic Oscillation (AO) is the dominant pattern of non-seasonal sea-level pressure variations north of 200 N latitude, and it is characterized by pressure anomalies of one sign in the Arctic with the opposite anomalies centered about 37-450 N. The AO appears to be related to changes in the strength of the winter stratospheric polar night jet [18]. The AO has been reported to have a strong influence on conditions over the central Arctic Ocean and lesser influence on the north Atlantic and north Pacific basins [45]. A relationship has been found between the AO and river discharge for rivers draining into Hudson Bay [12]. It has been found that the forecasts of AO could result in increased climate predictive skill in particular for runoff [26].

The AO is reported to be similar in structure to the North Atlantic Oscillation. The North Atlantic Oscillation (NAO) is the normalized difference in surface pressure between a station in the Azores and a station in Iceland. The NAO has been found to be related to changes in temperature and precipitation in North America [37], [31]. The North Pacific (NP) index provides a measure of the strength of the Aleutian low during the winter period. The NP was found to be related to streamflow variability in the western United States [38].

The Atlantic Multidecadal Oscillation (AMO) describes a cyclic variation in large-scale atmospheric flow and ocean currents in the north Atlantic Ocean and is derived from sea surface temperature anomalies. The AMO has been found to be correlated with predictable patterns of rainfall across the United States [16]. Positive AMO anomalies are related to lower rainfall in parts of North America and increased rainfall in north-west Europe [34]. Values for the climate indices were obtained from sources listed in [41].

IV. Methodology

The first step in the methodology employed here is to create data sets of extreme flow measures. The first and the second data set consisted of high flow event magnitudes and their corresponding date of occurrence, respectively. The high flow events have been computed by extracting the maximum flow value for each year of the analysis period. The corresponding date of occurrence of the high flow event is extracted for each year for each station to create the second data set. The third and the fourth data set comprised of the low flow events and their date of occurrences, respectively. For the extraction of low flow events, a water year with start date of July 1 has been defined. This was necessary to minimize the splitting of low flows across years. To create the third date set, the seven-day moving averages of the flow values were first computed. The minimum seven-day moving average for each year for each station was then extracted. The fourth data set was created by extracting data indicating the date on which the low flow event occurred in each year.

A composite analysis approach was used to identify linkages between extreme flow measures and climate indices [29], [48]. The approach involves determining the 10 highest and 10 lowest values of various climate indices from the data record. The procedure involves examining high and low values for the climate indices separately since climate signals can exhibit a strong connection in one phase but a weak connection in the opposite phase [29], [41]. The 10 largest and 10 smallest values for each climate index were determined and the extreme flow measures for each station were examined for the years associated with the 10 largest values and the years associated with the 10 lowest values. A resampling approach was applied to determine if the 10 values of extreme flow measures differed significantly from the series mean. The resampling approach involves random sampling, with replacement, of 10 values of an extreme flow measure from the historical data. This procedure was repeated 1000 times to create a distribution for the average of subsamples of 10 values from the complete sample. The average of the each random subsample was then compared with the average of the actual subsample computed using the composite analysis. The number of random subsamples that had an average value more extreme than the actual subsample was determined and probability levels associated with the observed subsample were computed. This procedure was repeated for each climate index.

V. Mann-Kendall Test

Parametric and non-parametric methods have been extensively applied for detection of trends. Excellent reviews of applications of parametric and non-parametric methods have been provided [35], [55]. Parametric tests are more powerful than the non-parametric ones, but there is an implicit assumption of normality of data that is seldom satisfied. Hydro-meteorological time series are often characterized by data that is not normally distributed, and therefore nonparametric tests are considered more robust compared to their parametric counterparts [25]. Mann-Kendall is the most widely applied non-parametric test for detecting a trend in the hydro-meteorological time series [39], [33]. The test is distribution-free and therefore no assumption regarding the distribution of data is needed. A major advantage of Mann-Kendall test is that it allows missing data and can tolerate outliers. Several researchers have employed Mann-Kendall test to identify trends in the hydro-meteorological variables with respect to climate change [3], [15], [1], [11], [8], [46].

Mann Kendall test is a ranked based approach that consists of comparing each value of the time series with the remaining in a sequential order. The statistic S is the sum of all the counting as given in (1)

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{Sgn}\,(x_j - x_k). \tag{1}$$

where

$$\mathrm{Sgn}\,(x_j - x_k) = \begin{bmatrix} 1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{bmatrix} \tag{2}$$

and x_j and x_k are the sequential data values, n is the length of the data set. A positive value of S indicates an upward and a negative value indicates a downward trend. For samples greater than 10, the test is conducted using normal distribution with the mean and variance as follows [24].

$$E[S] = 0 \tag{3}$$

$$\mathrm{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5) \right] \tag{4}$$

where, t_p is the number of data points in the p^{th} tied group and q is the number of tied groups in the data set. The standardized test statistic (Z_{mk}) is calculated by

$$Z_{mk} = \begin{bmatrix} \dfrac{S-1}{\sqrt{\mathrm{Var}\,(S)}} & \text{if } S > 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}\,(S)}} & \text{if } S < 0 \\ 0 & \text{if } S = 0 \end{bmatrix} \tag{5}$$

where the value of Z_{mk} is the Mann- Kendall test statistics that follows standard normal distribution with mean of zero and variance of one. Thus, in a two sided test for trend, the null hypothesis H_o is accepted if $-Z_{1-\alpha/2} \leq Z_{mk} \leq Z_{1-\alpha/2}$, where α is the significance level that indicates the trend strength. In the present study, significance levels of 5 and 10% are applied and the observed p-value is obtained for each analyzed time series.

The Mann-Kendall test has two parameters that are of relevance to trend detection. The first is the significance level that indicates the trend strength and the second is the slope magnitude estimate that indicates the direction as well as the magnitude of the trend. The presence of a positive serial correlation in a data set can increase the expected number of false positive outcomes for the Mann–Kendall test; the version of the trend test used herein incorporates a correction for serial correlation [52]. The calculated Mann-Kendall trend statistic is used to determine the significance of a trend in a data set, which is referred to as the local significance level for an individual site. For a collection of sites, the global (or field) significance of the individual results at the collection of sites is evaluated using a bootstrap resampling technique [4]. The results indicate whether a significant number of significant trends have been identified for a particular variable.

VI. Data And Study Area

The data used in this study are derived from the Canadian Reference Streamflow observations may be influenced by regulations and diversions upstream of a station. Therefore, it is important that stations with natural flow conditions are considered in the analysis. Stations from the RHBN are characterized by relatively pristine and stable land-use conditions (less than 5% of the surface modified) with a minimum of 20 years of record. RHBN stations were identified as suitable hydrometric gauging stations for climatic change investigations [23]. The RHBN originally consisted of over 200 active gauging stations; this work uses stations with a minimum, nominal record length of 50 years to ensure statistical validity of the trend results. There are 92 active stations in the RHBN with a nominal record length of 50 years. Sixty two gauging stations having a nominal record length of at least 50 years are analyzed for linkages with climate indices and for trends. The subset of 62 stations used herein was selected to provide a good geographic mix of stations and a range of watershed sizes.

Two common analysis periods were adopted for this work, with each period ending in 2006. The analysis periods are 45 years (1962 to 2006) and 40 years (1967 to 2006). The two analysis periods reflect a trade-off between greater spatial coverage with a shorter analysis period versus greater power for the statistical tests for a longer analysis period. A gauging station was included in an analysis period if no more than four years of record were missing for the duration of the analysis period. As a result of missing data, and stations for which recent data have not yet been released, the original 62 stations were reduced to 49 and 44 stations for the 40 and 45 year analysis periods, respectively.

VII. Application And Results

The results of applying the Mann-Kendall trend test to the extreme flow measures are summarized in Table 1. Shown in Table 1 are the percentage of stations showing a significant increasing trend and the percentage of stations showing a significant decreasing trend for the two analysis periods and for the four extreme event measures. Results are presented for the ten and five percent local significance levels, with the latter presented in brackets on the second line for each variable. Results that are field significant are shown in bold; the significance level for field significance was set to the same significance level as was used to identify local significance. Field significance was identified separately for increasing and decreasing trends following the recommendations in [52]. Apparent from Table 1 is the presence of more trends than can be expected to occur by chance (as determined by the field significance). The only variable that does not demonstrate field significance for at least one trend direction is LFT for the 45 year analysis period. Most of the extreme flow measures demonstrate consistent results for both analysis periods and when evaluated at the two significance levels.

TABLE I
PERCENTAGE OF STATIONS WITH A SIGNIFICANT TREND AT THE 10% SIGNIFICANCE LEVEL (5% SIGNIFICANCE LEVEL)

Variable	Analysis Period	
	1967 – 2006 (40 years)	1962 – 2006 (45 years)
High Flow Magnitude (HFM)	+4.1%/-16.4% (+4.1%/-8.2%)	+2.3%/-15.9% (+2.3%/-13.6%)
High Flow Timing (HFT)	+0.0%/-20.4% (+0.0%/-12.3%)	+0.0%/-18.2% (+0.0%/-9.1%)
Low Flow Magnitude (LFM)	+14.3%/-18.4% (+8.2%/-6.1%)	+13.6%/-18.2% (+11.4%/-11.4%)
Low Flow Timing (LFT)	+6.1%/-12.3% (+4.1%/-10.2%)	+0.0%/-9.1% (+0.0%/-2.3%)

Notes: Positive values indicate increasing trends and negative values indicate decreasing trends.
Entries in bold indicate results that are field significant.
The first line of results is for the 10% significance level and the second line (in brackets) is for the 5% significance level (both local and global).

The high flow events exhibit a significant number of decreasing trends in high flow magnitude and a significant number of decreasing trends in the high flow timing (earlier occurrence of the events). The low flow magnitude exhibits both a significant number of increasing trends and a significant number of decreasing trends, although the trends are more prevalent at the ten percent significance level. There is some evidence to suggest a shift in timing of low flow event towards earlier events, as can be seen from the LFT results for 40 years.

The question next arises as to whether the changes noted from Table 1 are a result of teleconnections with large-scale climate indices. Table 2 and Table 3 summarizes the results of the composite analysis for the six climate indices and the four extreme flow measures for the positive and negative

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phases respectively. From Table 3 it can be seen that the negative phase of the PDO, AO and NAO have more of an impact on the extreme flow measures than does the positive phase. The NP and AMO have more of an effect on the extreme flow measures during the positive phase than during the negative phase while the ENSO has roughly the same impact in both phases. Most of the extreme flow measures are more impacted by the negative phase of the climate indices than by the positive phase, with the exception of LFM, which has about the same impact in both phases. As a final step, the number of occurrences of both a significant trend and a relationship with a climate index were determined. The results are summarized in Table 4. Table 4 reveals that most of the stations and variables for which there are significant trends are not cases where there is a relationship between a climate index and an extreme flow measure. This suggests that the trends reported in Table 1 are, for the most part, not attributable to the impacts of the various climate indices investigated.

TABLE II
NUMBER OF STATIONS INFLUENCED BY POSITIVE PHASE OF CLIMATE INDICES

Extreme Flow Measure	Climate Indices					
	PDO	AO	NAO	NP	AMO	ENSO
HFM	3	3	0	4	2	1
HFT	2	1	5	2	2	2
LFM	0	1	1	7	11	4
LFT	3	3	1	0	2	3
Total	8	8	7	13	17	10

TABLE III
NUMBER OF STATIONS INFLUENCED BY NEGATIVE PHASE OF CLIMATE INDICES

Extreme Flow Measure	Climate Indices					
	PDO	AO	NAO	NP	AMO	ENSO
HFM	5	1	3	1	4	5
HFT	3	10	5	1	2	5
LFM	7	3	4	3	3	1
LFT	2	9	6	3	2	1
Total	17	23	18	8	11	12

TABLE IV
NUMBER OF STATIONS WITH A SIGNIFICANT TREND AND A RELATIONSHIP WITH A CLIMATE INDEX

Extreme Flow Measure	Climate Indices					
	PDO	AO	NAO	NP	AMO	ENSO
HFM	0+/1-	0+/0-	0+/0-	0+/0-	1+/1-	0+/1-
HFT	0+/1-	0+/3-	0+/0-	0+/1-	0+/1-	0+/2-
LFM	0+/1-	0+/0-	0+/1-	0+/2-	3+/0-	0+/1-
LFT	1+/1-	1+/0-	0+/0-	0+/0-	1+/0-	0+/0-

Note: "+" and "-" refer to increasing and decreasing trends, respectively.

VIII. Discussion And Conclusions

The results presented indicate changes are occurring in the flood regime for the sites examined, both in terms of the flood magnitudes (generally decreasing) and the timing of flood events (generally occurring earlier). As well, changes are occurring in the low flow regime with both increases and decreases in low flow magnitude and a weak indication of a decrease in low flow timing (earlier occurrence of low flow events).

While there are many stations where there is a relationship between an extreme flow measure and one of the large scale climatic indices examined, the results revealed that the climate indices can only partially explain the observed trend behaviour. This implies that at least some of the trend behaviour can be attributed to the impacts of global climate change.

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