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Evaluation of the capability of the Lombard test in detecting abrupt changes in variance

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SUMMARY

Hydrologic time series are often characterized by temporal changes that give rise to non-stationarity. When the distribution describing the data changes over time, it is important to detect these changes so that correct inferences can be drawn from the data. The Lombard test, a non-parametric rank-based test to detect change points in the moments of a time series, has been recently used in the hydrologic literature to detect change points in the mean and variance. Little is known, however, about the performance of this test in detecting changes in variance, despite the potentially large impacts that these changes (shifts) could have when dealing with extremes. Here we address this issue in a Monte Carlo simulation framework. We consider a number of different situations that can manifest themselves in hydrologic time series, including the dependence of the results on the magnitude of the shift, significance level, sample size and location of the change point within the series. Analyses are performed considering abrupt changes in variance occurring with and without shifts in the mean. The results show that the power of the test in detecting change points in variance is small when the changes are small. It is large when the change point occurs close to the middle of the time series, and it increases nonlinearly with increasing sample size. Moreover, the power of the test is greatly reduced by the presence of change points in mean. We propose removing the change in the mean before testing for change points in variance. Simulation results demonstrate that this strategy effectively increases the power of the test. Finally, the Lombard test is applied to annual peak discharge records from 3686 U.S. Geological Survey stream-gaging stations across the conterminous United States, and the results are discussed in light of the insights from the simulations' results.

1. Introduction

Hydrologists and water resources managers have been challenged by the non-stationarities in the hydrologic records. Milly et al. (2008) noted that "stationarity is dead" and cannot be assumed in modern design and management of hydraulic structures. It is clear that stationarity and the idea that the distribution of the variable of interest does not change over time is more of a working assumption (e.g., Hirsch, 2011; Lins and Cohn, 2011) and that its validity is not justified when working with "long" (centennial to millennial) records.

Hydrometeorological time series (e.g., rainfall, discharge) are said to be stationary if their distributions are invariant to translation in time (e.g., Brillinger, 2001), meaning that they do not exhibit gradual or abrupt changes or periodicities (e.g., Salas, 1993). Non-stationarity in hydrologic time series can be attributed to a number of factors, from natural variability of the climate system to human modifications of the watersheds. The presence of non-stationarities in hydrology complicates planning, operation and management of water systems and water resources. It also hinders accurate hydrologic modeling and forecasting which can have a large impact in our understanding of the nexus between water, ecological and social systems. Inferences regarding the uncertainty in future water availability, water usage, and water demand are difficult to make if we do not account for non-stationarity in the hydrologic data. Because of the problems arising from non-stationarity, it is imperative to detect them to avoid drawing conclusions that are not supported by the data.

Changes in hydrologic time series can result from complex processes, and the detection of these changes can be problematic and challenging. Many obstacles prevent accurate estimation of change points in hydrologic time series. Changes can occur in different moments (e.g., mean, variance) of the distribution of the variable

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of interest. Variance changes in a time series can obscure changes in the mean, and vice versa (e.g., Kundzewicz and Robson, 2004). Changes can be abrupt or gradual. Determining explicitly whether a change is abrupt or gradual, or if there is a trend present in the data, is an active research question that hydrologists and statisticians are working on (e.g., Rougé et al., 2013). Further complications in detecting change points in hydrologic time series are added by the not-so-unlikely presence of multiple change points and outliers, which have the potential of masking the presence of change points during the detection process. Further, the unknown number of changes and their locations add to the complexity of this problem. Hydrologic time series are usually highly skewed, potentially affecting the accurate detection of change point(s). Statistical methods to detect change points are particularly helpful as it is not always easy to understand physically how changes in different drivers (e.g., changes in land use/land cover) can lead to changes in the variable of interest (e.g., annual maximum discharge).

Over the past few decades, a number of methods have been developed to detect changes in the time series of interest. Parametric and non-parametric methods are available in both frequentist and Bayesian approaches (e.g., Barry and Hartigan, 1993; Lombard, 1987; Pettitt, 1979). For an extended review on change point analysis one can refer to Beaulieu et al. (2009), Brodsky and Darkhovsky (1993), Peterson et al. (1998), and Reeves et al. (2007). Of particular importance are the hydrometeorological extremes (e.g., heavy rainfall, flooding), which have an immediate and direct impact on the society and the ecosystems. In addition, small changes in extremes can be more impactful than similar changes in the averages. For example, small increase in the variance of annual maximum or annual minimum discharge can have larger impacts than the same amount of increase in the variance of the average flow. Modeling studies point to an acceleration of the hydrologic cycle with a projected increase in extremes (e.g., Held and Soden, 2006). Changes in the frequency and magnitude of flooding due to climate change are larger than the changes in the average precipitation (e.g., Knox, 1993). This is due to higher than average sensitivity of extremes to climate change (Knox, 1993). Hydrologic extremes, generally described using extreme value distributions, are highly skewed. This leads to high sensitivity of probabilities of extreme values to small changes in the parameters of the distributions. In hydrology, changes in mean and their impact on the quantiles of the distribution have been studied (Collins, 2009; Mallakpour and Villarini, 2015; Villarini et al., 2009b; Zhang et al., 2014) and a number of approaches have been proposed to identify these changes (Beaulieu et al., 2009; Kundzewicz and Robson, 2004; Rougé et al., 2013). However, the detection of changes in variance is still problematic despite the fact that changes in the variance for extremes are at least as important as the changes in means. For few non-normal distributions (often the case in hydrology) such as Gamma distribution, a change in variance causes a change in mean, and vice versa, as both of them depend on the location and scale parameters of the distribution. Variance increase leads to higher probability of occurrence of quantiles on both the upper and lower tails. In addition, extreme events, their frequency and magnitudes, are more sensitive to changes in variance than changes in mean (e.g., Ferro et al., 2005; Katz and Brown, 1992; Meehl et al., 2000). Katz and Brown (1992) showed that the changes in the frequency of extreme events are more dependent on the variability of the climate than its mean—the dependence increases as the events become more extreme. They verified the theoretical results on daily temperature series during July from a station in Des Moines, Iowa. They showed that the probability of extreme temperatures above 38 °C, which are of particular interest to Iowan farmers, increases (decreases) more than twice with variance increases (decreases) as compared to the similar changes in the mean. Schar et al. (2004) showed that the extreme heat wave of 2003 is not explained by a change in mean only, but by accounting for increased variability over time. They further noted that the European summer climate may experience substantial increases in year-to-year climate variability in the future. Brown and Lall (2006) argued that rainfall variability has been overlooked in devising plans for water sustainability. In understanding the role of water in the economic development, they showed that rainfall variability is a key factor that governs per capita gross domestic product of the nations—poor nations tend to have higher rainfall variability. Recently, Veldkamp et al. (2015) estimated the contribution of annual hydro-climatic variability to the regional and global water scarcity (measured in terms of water shortage and water stress). They concluded that hydro-climatic variability is the largest driver of change in yearly water scarcity, and that it is necessary to include it in water scarcity assessments. Many other studies stress the need to understand variance changes, especially when dealing with future climate (e.g., Ferro et al., 2005; Hansen et al., 2012; Mason and Calow, 2012).

While detecting changes in the mean is an important step toward correct inference, it is also critical to detect change points in variance. Therefore, the focus of this study is the detection of non-stationarities associated with the presence of abrupt changes in variance. These shifts are common in hydrology and can be associated, for instance, with the construction of dams and reservoirs, and changes in water policies and regulations, which take place over a relatively short period of time (e.g., McCabe and Wolock, 2002; Smith et al., 2010; Villarini et al., 2009a). Villarini et al. (2009a) analyzed annual peak flows from 50 stations over the conterminous United States that had a record of at least 100 years. They showed that the changes in streamflow were abrupt rather than gradual, and that apparent trends in the data were often caused by unidentified abrupt change points. In addition to streamflow, many studies point to abrupt changes in precipitation. Abrupt changes in the climate system have been shown to have rapid impact on precipitation extremes in certain regions (Chen et al., 2014; Zhang et al., 2014, 2009).

The negative effects of abrupt changes in mean and variance on flood frequency analysis are further exemplified in Fig. 1, which focuses on annual maximum discharge records for the Congaree River at Columbia, S.C. [U.S. Geological Survey (USGS) station ID 02169500]. The river flow has been regulated since October 1929 by the operation of the Saluda Dam at Lake Murray (Conrads et al., 2008). In the top panel of Fig. 1, change points in mean and variance are detected using Lombard test (Lombard, 1987; consult next section for more details on this test). The location of the change point in mean is estimated to be 1929, consistent with the year in which the Saluda Dam started operating. The location of the change point in variance is estimated to be 1935. The bottom panel of Fig. 1 shows the empirical cumulative distribution function (CDF) of the annual maximum peak discharge before and after the year of the change in variance. The shifts in the first two moments have caused a major change in the magnitude of large return period floods; for example, the 10-year flood magnitude before the change point has reduced to less than half after the construction of the dam (bottom panel).

For the detection of change points in variance, Bayesian, likelihood, and rank-based non-parametric approaches have been suggested. Before using a particular test or method, however, it is important to examine its performance so that users have some knowledge about the strengths, weaknesses and range of applicability of these tools. The objective of this paper is to evaluate the Lombard test (Lombard, 1987) for the detection of change points