Research papers

The influence of watershed characteristics on spatial patterns of trends in annual scale streamflow variability in the continental U.S.

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ABSTRACT

As human activity and climate variability alter the movement of water through the environment the need to better understand hydrologic cycle responses to these changes has grown. A reasonable starting point for gaining such insight is studying changes in streamflow given the importance of streamflow as a source of renewable freshwater. Using a wavelet assisted method we analyzed trends in the magnitude of annual scale streamflow variability from 967 watersheds in the continental U.S. (CONUS) over a 70 year period (1940–2009). Decreased annual variability was the dominant pattern at the CONUS scale. Ecoregion scale results agreed with the CONUS pattern with the exception of two ecoregions closely divided between increases and decreases and one where increases dominated. A comparison of trends in reference and non-reference watersheds indicated that trend magnitudes in non-reference watersheds were significantly larger than those in reference watersheds. Boosted regression tree (BRT) models were used to study the relationship between watershed characteristics and the magnitude of trends in streamflow. At the CONUS scale, the balance between precipitation and evaporative demand, and measures of geographic location were of high relative importance. Relationships between the magnitude of trends and watershed characteristics at the ecoregion scale exhibited differences from the CONUS results and substantial variability was observed among ecoregions. Additionally, the methodology used here has the potential to serve as a robust framework for top-down, data driven analyses of the relationships between changes in the hydrologic cycle and the spatial context within which those changes occur.

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1. Introduction

The movement of water is a primary agent for the transport of mass and energy around the Earth, and is critically important to many of the Earth's systems. Hydrologic fluxes provide couplings between the water, energy, and biogeochemical cycles, influence the function of the climate system, and provide critical support for living organisms (Vorosmarty et al., 1998; Jackson et al., 2001; Rodriguez-Iturbe and Porporato, 2004; Bonan, 2008). As a result, water is entwined with a variety of complicated geopolitical and socioeconomic issues around the globe (Wagener et al., 2010; NRC, 2012). This is especially true where temporal and spatial changes in the movement of water, over a variety of scales, are involved (Sivapalan and Kalma, 1995). Understandably, the generation of knowledge concerning changes in the movement of water has been identified as a key challenge in the hydrologic sciences (NRC, 2012).

Changes in streamflow have been a frequent focus of past work examining changes in the terrestrial portion of the hydrologic cycle, particularly in the continental United States (CONUS) where long-term streamflow records are readily available. A general pattern of increasing streamflow at the CONUS scale has been reported in multiple studies (e.g., Lettenmaier et al., 1994; Lins and Slack, 1999). Declines in streamflow have also been reported in analyses specific to individual regions (e.g., Luce and Holden, 2009; Patterson et al., 2012). Changes in streamflow variability, particularly in the western U.S., have also been reported in several studies (Jain et al., 2005; Pagano and Garen, 2005). Additional studies reporting little evidence of changes in annual maxima (Villarini and Smith, 2010), a mix of increasing and decreasing annual maxima (McCabe and Wolock, 2002), and significant increases in flood risk (Hamlet and Lettenmaier, 2007) are all present in the literature.

Existing research on streamflow trends has focused heavily on time domain analysis (e.g., changes in annual means or maxima, or variability within discrete time intervals). Such work has improved our understanding of these systems, but research is

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currently lacking concerning widespread, long-term changes in the periodic structure of streamflow time series. The periodic structure of streamflow time series provides insight into the envelope of hydrologic variability created by the relative disparity between recurring cycles of dry and wet phases. Examining trends in this behavior considers both potential collapse and widening in this envelope of hydrologic variability, depending on the direction of the trend. This information from the frequency domain provides an important complement to time domain approaches to studying streamflow variability, such as changes in variance within a discrete time interval. Traditional frequency domain analyses, such as the Windowed Fourier Transform, may encounter issues when applied to geophysical data, such as streamflow, due to nonstationarity, intermittent periodicities, and the need for scale dependent time and frequency localization (Torrence and Compo, 1998; Coulibaly and Burn, 2004; Grinsted et al., 2004; Labat, 2005).

The wavelet transform overcomes many of the aforementioned issues and has seen use as a tool for the analysis of hydrologic time series (e.g., Smith et al., 1998; Coulibaly and Burn, 2004; Labat et al., 2005; Labat, 2008; Molini et al., 2010). Wavelet based methods provide a particularly advantageous option for the analysis of geophysical time series as the underlying process need not be stationary and the one dimensional signal can simultaneously be examined in the time and frequency domains across a range of scales (Lau and Weng, 1995; Torrence and Compo, 1998; Grinsted et al., 2004). Wavelet based analyses thus provide an attractive option for analyzing the regularly occurring periodic behavior of geophysical time series, such as streamflow, and how such behavior may vary, or change, over time (Torrence and Compo, 1998; Labat, 2005; Nalley et al., 2012). While wavelet based analyses have received some criticism in the past due to a perceived lack of quantitative results (see Torrence and Compo, 1998), the coupled application of wavelet methods and more traditional techniques for assessing trends in streamflow has been successfully used in a number of recent studies (e.g., Zhang et al., 2006; Adamowski et al., 2009; Nalley et al., 2012; Sang et al., 2012).

Much of the past work examining changes in streamflow has focused on large scale patterns and the potential influence of climatic processes on those changes (e.g., Lettenmaier et al., 1994; Hamlet and Lettenmaier, 2007; Patterson et al., 2013; Luce et al., 2013). While such methods provide understanding of the relationship between streamflow and large scale forces, they provide limited knowledge concerning the influence of the internal characteristics of watersheds. As internal watershed features help define the state of the interface between the atmospheric and terrestrial portions of the hydrologic cycle, studying their impact on changes in the transport of water may prove insightful (Emanuel et al., 2010). An often presented method of studying watershed specific features involves a spatially explicit quantification of variables describing the physical setting in which watersheds function (Winter, 2001; Sivapalan et al., 2003; McDonnell and Woods, 2004; Wagener et al., 2007).

In this paper we examine changes in the magnitude of annual scale streamflow variability and relationships between the degree of those changes and watershed scale spatial features involved in defining the physical and hydrological context of individual watersheds. We focus specifically on the periodic behavior of streamflow as this behavior represents a predictable aspect of how the function of these systems change over time. Such information is complementary to a recent study focused on changes in streamflow at discrete time intervals (e.g., Rice et al., 2015) and fills an important gap in current knowledge considering overall changes in streamflow behavior. In addressing this knowledge gap, this research will explore two primary questions concerning changes in the frequency domain behavior of streamflow: First, what patterns emerge in changes in the magnitude of annual scale streamflow variability across the continental U.S. (CONUS) between 1940 and 2009? And second, how are the characteristics of individual watersheds related to variation in the magnitude of those trends and how do these relationships vary spatially? By exploring temporal changes in the periodic behavior of streamflow, and controls on those changes, we hope to improve our basic understanding of these systems as well as bolster current capabilities to forecast future changes.

2. Methods

2.1. Data overview

This study uses the same set of watersheds analyzed by Rice et al. (2015), who focused on long-term changes in daily streamflow across the CONUS. This dataset consists of 967 watersheds within the CONUS (Fig. 1) chosen from the USGS GAGES-II dataset, which contains highly scrutinized geospatial data for a set of gaged watersheds in the United States (Falcone et al., 2010a). We limited our analysis to GAGES-II watersheds with streamflow data for the 70-year period from 1940 to 2009 that were at least 90% complete, and we included reference and non-reference status watersheds. These reference watersheds are those whose hydrological processes are considered minimally impacted by human activity within the watershed (Lins, 2012). By including non-reference watersheds, we present an analysis that represents more accurately the widespread influence of anthropogenic activity on the hydrologic cycle (Dynesius and Nilsson, 1994; Nilsson et al., 2005; Villarini et al., 2009; Villarini and Smith, 2010). The study watersheds cover nine aggregated level two ecoregions, as classified by the GAGES-II dataset (Fig. 1).

2.2. Wavelet transform and streamflow trends

Our analysis of trends in streamflow was centered on time series of total monthly runoff, derived from mean daily streamflow observations from each of the 967 gaged watersheds included in the study dataset. Missing data points in the total monthly runoff series were imputed using the median value of the month in question (n = 1109 data points, or 0.14%). Prior to analyzing trends, the continuous wavelet transform (CWT) was applied to each streamflow time series to quantify the magnitude of annual scale variations while still accounting for periodic behavior at other scales. Annual scale variability has been a focus of previous work utilizing the CWT and streamflow data as it tends to be a dominant mode of variability in many streams (Adamowski et al., 2009), including much of the data considered here. The CWT was applied here, rather than the discrete wavelet transform, as it has previously been shown to be an effective tool for the extraction of information from geophysical time series (e.g., Lau and Weng, 1995; Torrence and Compo, 1998; Grinsted et al., 2004). For a comprehensive discussion of the CWT we refer to one of many excellent discussions on the topic (e.g., Lau and Weng, 1995; Torrence and Compo, 1998; Labat, 2005).

In this study the Morlet wavelet (Morlet et al., 1982) was used as the mother wavelet function due to its proven effectiveness in analyzing hydrological time series (e.g., Kang and Lin, 2007; Adamowski et al., 2009) and its ability to strike a balance between time and frequency localization (Lau and Weng, 1995; Grinsted et al., 2004). The shifted and scaled Morlet mother wavelet is defined as:

$$\psi_{a,b}^l(s) = \pi^{-1/4}(al)^{-1/2}e^{-i2\pi}e^{-1/2\left(\frac{s-b}{al}\right)^2} \tag{1}$$