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Trends in snowmelt-related streamflow timing in the conterminous United States

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ABSTRACT

Changes in snowmelt-related streamflow timing have implications for water availability and use as well as ecologically relevant shifts in streamflow. Historical trends in snowmelt-related streamflow timing (winter-spring center volume date, WSCVD) were computed for minimally disturbed river basins in the conterminous United States. WSCVD was computed by summing daily streamflow for a seasonal window then calculating the day that half of the seasonal volume had flowed past the gage. We used basins where at least 30 percent of annual precipitation was received as snow, and streamflow data were restricted to regionally based winter-spring periods to focus the analyses on snowmelt-related streamflow. Trends over time in WSCVD at gages in the eastern U.S. were relatively homogenous in magnitude and direction and statistically significant; median WSCVD was earlier by 8.2 days (1.1 days/decade) and 8.6 days (1.6 days/decade) for 1940–2014 and 1960–2014 periods respectively. Fewer trends in the West were significant though most trends indicated earlier WSCVD over time. Trends at low-to-mid elevation (<1600 m) basins in the West, predominantly located in the Northwest, had median earlier WSCVD by 6.8 days (1940–2014, 0.9 days/decade) and 3.4 days (1960–2014, 0.6 days/decade). Streamflow timing at high-elevation ($\geqslant$1600 m) basins in the West had median earlier WSCVD by 4.0 days (1940–2014, 0.5 days/decade) and 5.2 days (1960–2014, 0.9 days/decade). Trends toward earlier WSCVD in the Northwest were not statistically significant, differing from previous studies that observed many large and (or) significant trends in this region. Much of this difference is likely due to the sensitivity of trend tests to the time period being tested, as well as differences in the streamflow timing metrics used among the studies. Mean February–May air temperature was significantly correlated with WSCVD at 100 percent of the study gages (field significant, $p < 0.0001$), demonstrating the sensitivity of WSCVD to air temperature across snowmelt dominated basins in the U.S. WSCVD in high elevation basins in the West, however, was related to both air temperature and precipitation yielding earlier snowmelt-related streamflow timing under warmer and drier conditions.

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1. Introduction

1.1. Importance of snowmelt-related streamflow timing

The timing of snowmelt-related streamflow is as important as the overall quantity and quality of water, for both ecosystem health and human uses (Dettinger and Cayan, 1995). Where snowmelt is a substantial fraction of available water, earlier melt and runoff can decrease water availability later in the year, impacting agriculture, ecosystems, and frequency and occurrence of wildfires (Hall et al., 2015). Westerling (2016) attributed significant increases in the frequency of large wildfires in the Northern Rocky Mountains and Pacific Northwest over recent decades to changes in moisture deficit associated with snowmelt-related streamflow timing—computed as the date of the center of mass of annual streamflow (CTI) at snowmelt-dominated basins. During 1970–2012, the earliest third of CTI values were associated with 70 percent of the total area burned by large forest fires, and 43 percent of the total area burned in non-forest fires (Westerling, 2016).

As much as 75 percent of water supplies in the western United States are derived from snowmelt (Dettinger, 2005). It is estimated that by 2050, future climate-change related warming will have a substantial impact on water supply in the western U.S because of

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a large reduction of snowpack (natural storage) and earlier spring peak streamflow (Barnett et al., 2005). Stewart et al. (2004) estimated that snowmelt-related streamflow timing in western North America during 2040–2059 may be about two to four weeks earlier relative to a 1951–1980 reference period. Roy et al. (2012) anticipated that approximately one-third of counties will be at high or extreme risk of water shortages by the year 2050 on the basis of estimated future water use and climate conditions. Concerns include whether reservoir storage in most of the western U.S. is adequate to handle the earlier peak streamflow and meet competing water use interests—for example hydropower generation vs. federally protected salmon in the Northwest (Barnett et al., 2005).

In the eastern United States, impacts of earlier snowmelt-related streamflow timing are less clear, as snowmelt is normally complete by May and summer rainfall generally is abundant (Hodgkins and Dudley, 2006). Spring peak flows in the Northeast are projected to become earlier by about a week by mid-century relative to a 1961–1990 reference period (Hayhoe et al., 2007). Changes in snowmelt-related streamflow timing may be important though, for example, if peak spring migration of the endangered Atlantic salmon (which is partially dependent on flow) becomes out of phase with optimal environmental conditions, salmon survival could drop substantially (McCormick et al., 1998).

1.2. Trends in snowmelt-related streamflow timing

Climate-change indicators of snowmelt-related streamflow provide means for improved understanding of temperature-related effects on streamflow. Air temperatures in the United States during the past century have been related to observed changes in snow-to-rain ratios, snowpack, and timing of snowmelt-related streamflow (Regonda et al., 2005; Stewart et al., 2005; McCabe and Clark, 2005; Hodgkins and Dudley, 2006). Historical trends in the timing of snowmelt-related streamflow have been well studied, particularly in the western United States, where several studies have analyzed a large number of basins for most of the second half of the 20th century (Aguado et al., 1992; Cayan et al., 2001; Regonda et al., 2005; Stewart et al., 2005; McCabe and Clark, 2005; Westerling et al., 2006; Fritze et al., 2011; U.S. Environmental Protection Agency, 2014; Westerling, 2016). Other studies in the West have analyzed streamflow timing for specific regions (Dettinger and Cayan, 1995; Clow, 2010; Clark, 2010; Pederson et al., 2011). In the eastern United States, studies have covered extensive geographic areas (Hodgkins and Dudley, 2006; U.S. Environmental Protection Agency, 2014) and more specific regions (Hodgkins et al., 2003; Burns et al., 2007). Ryberg et al. (2015) studied many basins in the north-central U.S.

In the western U.S., there were widespread changes during the second half of the 20th Century toward earlier snowmelt-related streamflow timing, and very few basins with significantly later streamflow timing in the West (Regonda et al., 2005; Stewart et al., 2005; McCabe and Clark, 2005; Fritze et al., 2011). The highest number of significant changes were in the Northwest; many basins had non-significant trends in the interior West. Regonda et al. (2005) found 10–20 day changes toward earlier snowmelt-related streamflow timing during 1950–1999 to be common for basins under 2500 m in elevation and little consistent change for basins over 2500 m; McCabe and Clark (2005) also found that streamflow-timing trends were significantly related to elevation. In the eastern U.S., there were widespread changes toward earlier timing of snowmelt-related streamflow north of 44° North latitude, with the highest number of significant changes in northern New England (Hodgkins and Dudley, 2006).

Stewart et al. (2005) observed significant negative correlations (generally $-0.8 \leqslant r \leqslant -0.3$) between spring air temperatures and snowmelt-related streamflow timing at basins throughout the western U.S. (warmer temperatures associated with earlier dates). The correlations between streamflow timing and temperature were largely unchanged when the variance related to precipitation was removed. Streamflow timing was positively correlated with total winter precipitation in most of the West (more precipitation associated with later dates), and negatively correlated in parts of the Northwest and Southwest (Stewart et al., 2005).

Regonda et al. (2005) documented significantly earlier spring warm spells and increased precipitation over much of the western U.S. Decreases in winter precipitation in the Northwest combined with increases in spring temperatures appeared to have had a strong impact on snowmelt-related streamflow timing. Increased winter precipitation in the interior West may have offset increased air temperature and led to fewer or smaller changes in the timing of snowmelt-related streamflow. Regonda et al. (2005) also found that changes in snowpack water equivalent in the western U.S. are sensitive to the effects of temperature, but primarily in basins below about 2500 m.

In the eastern U.S., Hodgkins et al. (2003) found that air temperatures had much higher correlations with New England snowmelt-related streamflow timing than precipitation. The highest correlation with seasonal air temperatures was with March-April temperatures ($r = -0.72$) while the highest correlation with precipitation was with January precipitation ($r = -0.37$).

Temperatures across the U.S. have increased overall by 0.7–1.1 °C since 1895 (Karl et al., 2009; Menne et al., 2010; Vose et al., 2012; Williams et al., 2012). Over this same period, average annual precipitation over the U.S. has increased by roughly 5 percent. This overall increase reflects, in part, a relatively dry early half of the record due to the major droughts of the 1930s and 1950s. Regionally, precipitation since 1991 (relative to 1901–1960) increased the most in the Northeast (8 percent), Midwest (9 percent), and southern Great Plains (8 percent), while much of the Southeast and Southwest had a mix of areas of increases and decreases (McRoberts and Nielsen-Gammon, 2011; Peterson et al., 2013).

Several regional studies have documented decreasing annual and seasonal ratios of snowfall to precipitation in the U.S. (Knowles et al., 2006; Feng and Hu, 2007; Huntington et al., 2004), and total snowfall has decreased in many parts of the U.S. based on widespread observations since 1930 (Kunkel et al., 2009). Studies have shown that snowpack over the past half century declined in most of the mountainous western U.S. concurrent with higher winter and spring air temperatures. Mote et al. (2005) reported that climate trends are the dominant factor in widespread declines in spring snowpack in the western U.S. during 1950–97. Hamlet et al. (2005) found most of the change in spring snowpack in the Rocky Mountains was attributed to increasing air temperatures rather than changes in precipitation, which were relatively small.

Much of the climate variability in the western U.S. is driven by Pacific climate patterns and snowmelt-related streamflow timing has a significant negative correlation with the Pacific Decadal Oscillation (PDO) for many basins (Stewart et al., 2005). Streamflow timing had a significant positive association with the Southern Oscillation Index for some basins in the Northwest and a significant negative association for many basins in the southwestern U.S. from 1948 to 2002 (Stewart et al., 2005). McCabe and Clark (2005) found a modest but significant relation between snowmelt-related streamflow timing and PDO and a weaker but still significant relation with Niño-3.4 sea-surface temperatures (region in the equatorial Pacific Ocean bounded by 5° North–5° South and 170–120°West), indicating that PDO and El-Niño Southern Oscillation (ENSO) account for a small part of streamflow timing variability. We know of no published work on the relation between