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Detection of earlier snowmelt in the Wind River Range, Wyoming, using Landsat imagery, 1972–2013

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ABSTRACT

In the western United States snow has been melting earlier in recent decades due to warmer winter and spring weather. This is particularly noticeable in the Pacific Northwest and coastal areas, yet has been less obvious in locations farther inland. Using the historical Landsat image archive, snow cover was mapped in the Wind River Range (WRR) in northwestern Wyoming, from 1972–2013. The objective of this work was to estimate the temporal change in the rate of snowmelt in the Fremont Lake basin of the WRR for the 42-year study period. Much of the streamflow in Wyoming originates from melting snow in the WRR. Streamflow is a significant contributor to the water resources for the north-central part of the state and has tremendous societal and economic impacts especially during the prolonged drought that is affecting the western U.S. Consistent with the ongoing and severe drought, data from the Pine Creek Above Fremont Lake gauge show a striking reduction in cumulative stream discharge in the 2000s vs. the decades of the 1970s, 1980s and 1990s. Snow-cover depletion curves derived from snow maps created from Landsat imagery were generated for the period 1972–2013. MODerate-Resolution Imaging Spectroradiometer (MODIS)-derived standard snow-cover maps were also used to generate snow-cover depletion curves, from 2000–2013, to provide an accuracy assessment of the Landsat technique. Landsat-derived mean snow-cover depletion curves from 2000–2013 and from the three previous decades, show that snow cover in the Fremont Lake basin is melting 16 ± 10 days earlier, on average, in the 2000s compared to the period from 1972–1999. Increasing spring and summer nighttime air temperature is the likely driver of the earlier snowmelt documented in the Landsat record.

1. Introduction and background

Observational evidence from satellite data shows that snow has been melting earlier across the Northern Hemisphere since at least the middle of the twentieth century perhaps in response to a poleward amplification of warming and changes in atmospheric circulation (e.g., Derksen & Brown, 2012; Déry & Brown, 2007; Foster, 1989; Groisman, Karl, & Knight, 1994). The area of spring snow cover in the Northern Hemisphere is expected to continue to decrease during the twenty-first century (IPCC — Intergovernmental Panel on Climate Change: the Physical Science Basis, Summary for Policymakers, 2013). However the amount of change in snow cover has not been uniform, with greater spring snow-cover decreases evident in Eurasia vs. North America (e.g., Liston & Hiemstra, 2011).

Trends of increasing temperature over the western U.S. during the twentieth century have been observed (e.g., Dettinger, Cayan, Meyer, & Jeton, 2004; Stewart, Cayan, & Dettinger, 2005). Declining springtime snow-water equivalent (SWE) and warmer winter and spring weather have been documented in the western United States from 1925–2000; this is especially evident since the mid-twentieth century (Hamlet, Mote, Clark, & Lettenmaier, 2005; Mote, Hamlet, Clark, & Lettenmaier, 2005). The fraction of annual streamflow derived from snowmelt that runs off during late spring and summer in many high-elevation streams has declined by 10–25% since the 1950s (Cayan, Dettinger, Kammerdiener, Caprio, & Peterson, 2001). Warmer air temperatures also may be associated with lower snow-cover extent and SWE since more precipitation falls as rain when temperatures warm. Across much of the western U.S., the date of snowmelt onset has been reported to be earlier by up to, or more than, 20 days as compared to the mid-twentieth century (Stewart et al., 2005; USGS, 2005; Lundquist, Dettinger, Stewart, & Cayan, 2009). For river basins with substantial snow accumulation, modeled scenarios of increasing winter and spring temperatures are likely to result in increased winter runoff, reduced peak SWE, earlier peak streamflow and reduced summer streamflow volumes (e.g., Cayan, 1996; Cayan et al., 2001; Dettinger et al., 2004; Mote et al., 2005).

The western U.S. has been undergoing a severe to moderate drought since ~1999. Greater demands for water in the western U.S. have

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rendered the water-supply systems increasingly vulnerable to the impacts of drought (Woodhouse, Meko, MacDonald, Stahle, & Cook, 2010). Severe drought is the greatest recurring natural disaster in North America (Cook, Seager, Cane, & Stahle, 2007; Woodhouse et al., 2010), leading to water supply deficits, wildfires and other factors that impact growing population centers. Sustained drought conditions have resulted in water supply deficits in reservoir storage, e.g., in Arizona, New Mexico, Nevada, Utah and Wyoming (Cook et al., 2007; USDA, 2004). During 2012–2013, drought conditions in Wyoming ranged from moderate to abnormally dry but were largely 'extreme' to 'exceptional' http://www.wrds.uwyo.edu/sco/drought/droughttimeline.html. Most of the water supply in Wyoming comes from winter snowfall in the mountains, which has generally declined during the 2000s. Snow-fed streamflow in the Wind River Range (WRR) provides a large portion of the water resources for the north-central part of Wyoming (Watson, Barnett, Gray, & Tootle, 2009).

There is evidence of warming temperatures in the WRR. The temperature at an elevation of 4000 m increased by 3.5 °C between the mid-1960s and the early 1990s, as determined from ice cores by Naftz et al. (2002). Previous work by Hall, Foster, DiGirolamo, and Riggs (2012) found that air temperatures in the WRR had increased significantly at some stations from 1970 to 2009, although there was no trend showing earlier start or completion date of snowmelt *within* the decade of the 2000s according to MODIS-derived snow-cover depletion curves. However, a notable decrease in stream discharge occurred compared to the three previous decades, in all streams studied in the WRR (Hall et al., 2012).

It has been difficult to document decreases in snow cover in some basins in the WRR because easily-accessible, daily snow-cover maps have only been available since February of 2000 from the MODerate-Resolution Imaging Spectroradiometer (MODIS). Earlier satellite data from the Advanced Very High Resolution Radiometer, beginning in 1998, and the Landsat series, beginning in 1972, had previously been problematic to obtain. Furthermore, the earliest Landsat data from the Multispectral Scanner (MSS) beginning in 1972 is not ideal for snow-cover mapping because the MSS sensor lacked a short-wave infrared (IR) band which is useful for snow-cloud discrimination. A short-wave IR band has been included on all subsequent Landsat instruments. Furthermore, the repeat cycle of the first three Landsat satellites was only once every 18 days (Table 1).

Snow-cover depletion curves are useful and even required for input to many snowmelt models such as the Snowmelt–Runoff Model (SRM) (Martinec, Rango, & Roberts, 2008). Snow-cover depletion curves depict the temporal evolution of the snow-cover fraction for a given area (Déry et al., 2005) by plotting percent snow cover in a basin during the snowmelt period. The shape of the curves provides information about the rate and timing of snowmelt.

Our hypothesis is that snow cover and streamflow have been decreasing in the WRR since the 1970s due to warmer temperatures and lower snowfall amount. The objective of this work is to estimate the temporal change in the rate of snowmelt and snowmelt completion in the Fremont Lake Basin of the WRR. For the present study, we developed snow-cover depletion curves from Landsat data using curve-fitting to fill in gaps created because of the repeat cycle of the Landsat satellites, and we evaluated stream discharge, precipitation, snow-water equivalent (SWE) and air temperature records from 1970–2013 in the Fremont Lake basin of the WRR. By using both the Landsat and MODIS archives we are able to measure snowmelt trends for a 42-year study period and assess the accuracy of the methodology.

Table 1
Operating years along with repeat coverage and primary instruments of Landsat satellites: Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) [http://landsat.gsfc.nasa.gov/].

Name	Operating years	Repeat coverage	Primary instrument
Landsat-1	1972–1978	18 days	MSS
Landsat-2	1975–1982	18 days	MSS
Landsat-3	1978–1983	18 days	MSS
Landsat-4	1982–2001	16 days	MSS & TM
Landsat-5	1984–2013	16 days	MSS & TM
Landsat-7	1999–present	16 days	ETM+
Landsat-8	2013–present	16 days	OLI

2. Study area

The Wind River Range, located in northwestern-central Wyoming, is approximately 210 km long (Fig. 1a). Gannett Peak is the highest peak in the WRR at 4205 m. Sixty three small glaciers are found mostly on the eastern flank of the Continental Divide in the WRR, and have been in recession since at least 1966 (Bell, Tootle, Pochop, Kerr, & Sivanpillai, 2012; Cheesbrough, Edmunds, Tootle, Kerr, & Pochop, 2009; Pelto, 2011; Pochop, Marston, Kerr, & Varuska, 1989; Pochop et al., 1990; Thompson, Tootle, Kerr, Sivanpillai, & Pochop, 2011; VanLooy, Forster, Barta, & Turrin, 2013 & 2014; VanLooy, Miège, Vandberg, & Forster, 2014). Over time, loss of alpine glaciers will reduce the amount of water available for agricultural and domestic use (Cable, Ogle, & Williams, 2011). As an example, the Continental Glacier in the WRR, which has been studied intensively by VanLooy et al. (2013 and 2014), has experienced a reduction in elevation and volume between 1966 and 2012.

Most of the meltwater from snowpacks and glaciers in the WRR drains into the Wind-Big Horn River on the eastern slope of the Continental Divide, and then to the Missouri–Mississippi River system (VanLooy et al., 2014). Water to the west of the Continental Divide drains into the Green River on its way to the Colorado River. The Fremont Lake basin (202 km^2) is on the western side of the Continental Divide and is located north of Pinedale, Wyoming, and Fremont Lake (Fig. 1a & b). We focus on this basin because of the availability of National Oceanic and Atmospheric Administration (NOAA) meteorological station data in nearby Pinedale and a stream gauge at Pine Creek above Fremont Lake.

3. Data and methodology

The following satellite data were used in the present study: Landsat images from 1972 through 2013 at spatial resolutions ranging from 30 to 80 m, and MODIS Collection 6 (C6) daily snow-cover surface-reflectance-based maps at 500-m resolution, also known as MOD10A1S (Riggs & Hall, 2015). Daily stream discharge data for the Pine Creek Above Fremont Lake gauge, daily temperature and daily precipitation records from the meteorological station at Pinedale, and daily SWE measurements from SNOw TELemetry (SNOTEL) stations in the WRR were also analyzed.

3.1. Landsat snow-cover maps

Landsat MSS, Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI) images from 1972–2013 were used to map the percentage of snow cover in the Fremont Lake basin. MSS scenes from Landsats-1 and -3 covering the WRR are provided as path/row: 40/30 (1972–1982), while TM, ETM+ and OLI scenes are provided as path/row 37/30. We searched the U.S. Geological Survey (USGS) archive at the Earth Resources Observation and Science (EROS) Data Center [http://glovis.usgs.gov/] for MSS, TM, ETM+ and OLI scenes for day of year (DOY) 60–260 (approximately March through mid-September), from 1972–2013. We rejected most of the Landsat scenes due to cloud-related issues. Although the Landsat satellites had or have a repeat coverage of once every 16 or 18 days, acquisitions by two sensors, for example MSS and TM, TM and ETM+ or ETM+ and OLI, often result in more-frequent coverage especially later in the study period.