Atmospheric Environment xxx (2016) 1–12

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Increasing aeolian dust deposition to snowpacks in the Rocky Mountains inferred from snowpack, wet deposition, and aerosol chemistry

David W. Clow [a, *], Mark W. Williams [b], Paul F. Schuster [c]

[a] Colorado Water Science Center, United States Geological Survey, Denver Federal Center, MS 415, Denver, CO 80225, USA
[b] Department of Geography, University of Colorado at Boulder, UCB 360, Boulder, CO 80309, USA
[c] National Research Program, United States Geological Survey, 3215 Marine St., Boulder, CO 80303, USA

HIGHLIGHTS

- Snowpack calcium can be used as a surrogate for aeolian dust deposition to snow.
- Aeolian dust deposition to snow increased 81% in the southern Rockies during 1993–2014.
- Snowmelt timing accelerated 7–18 days over this time period in the Rockies, primarily due to changes in snowfall and dust deposition.

ARTICLE INFO

Article history:
Received 1 April 2016
Received in revised form
22 June 2016
Accepted 29 June 2016
Available online xxx

Keywords:
Aeolian
Carbonate
Dust
Snow
Trends
Snowmelt

ABSTRACT

Mountain snowpacks are a vital natural resource for ~1.5 billion people in the northern Hemisphere, helping to meet human and ecological demand for water in excess of that provided by summer rain. Springtime warming and aeolian dust deposition accelerate snowmelt, increasing the risk of water shortages during late summer, when demand is greatest. While climate networks provide data that can be used to evaluate the effect of warming on snowpack resources, there are no established regional networks for monitoring aeolian dust deposition to snow. In this study, we test the hypothesis that chemistry of snow, wet deposition, and aerosols can be used as a surrogate for dust deposition to snow. We then analyze spatial patterns and temporal trends in inferred springtime dust deposition to snow across the Rocky Mountains, USA, for 1993–2014. Geochemical evidence, including strong correlations ($r^2 \geq 0.94$) between Ca^{2+}, alkalinity, and dust concentrations in snow deposited during dust events, indicate that carbonate minerals in dust impart a strong chemical signature that can be used to track dust deposition to snow. Spatial patterns in chemistry of snow, wet deposition, and aerosols indicate that dust deposition increases from north to south in the Rocky Mountains, and temporal trends indicate that winter/spring dust deposition increased by 81% in the southern Rockies during 1993–2014. Using a multivariate modeling approach, we determined that increases in dust deposition and decreases in springtime snowfall combined to accelerate snowmelt timing in the southern Rockies by approximately 7–18 days between 1993 and 2014. Previous studies have shown that aeolian dust emissions may have doubled globally during the 20th century, possibly due to drought and land-use change. Climate projections for increased aridity in the southwestern U.S., northern Africa, and other mid-latitude regions of the northern Hemisphere suggest that aeolian dust emissions may continue to increase, compounding the risk that climate warming poses to snowpack water resources in arid/semi-arid regions of the world.

1. Introduction

Mountain snowpacks are a critical resource in arid and semi-arid regions of the world, with more than one-sixth of the world's population relying on snowmelt for their water supply (Barnett et al., 2005). Snowpacks are a large natural reservoir,

* Corresponding author.
E-mail address: dwclow@usgs.gov (D.W. Clow).

http://dx.doi.org/10.1016/j.atmosenv.2016.06.076

storing water during winter and releasing it during the summer and fall, when human and ecological demands are greatest (Barnett et al., 2008). Current and projected climate warming poses a substantial risk to snowpack resources, causing shifts in precipitation regime from snow to rain (Knowles et al., 2006), and shifting the timing of snowmelt towards earlier in the year (Cayan et al., 2001; Rauscher et al., 2008; Stewart, 2009; Clow, 2010). A recent study identified portions of southern Europe, the Middle East, and western North America as areas where climate-induced changes in snowpack resources may pose a substantial risk to summer/fall water supplies (Mankin et al., 2015).

Many of these areas are downwind from major sources of aeolian dust, which, when deposited on snow, can further accelerate snowmelt through increased absorption of solar energy (Conway et al., 1996; Painter et al., 2012; Skiles et al., 2012). Although uncertainties are high due to limited data, paleorecords suggest that desert dust emissions may have doubled across much of the globe during the 20th century (Mahowald et al., 2010), compounding the risk posed by climate warming to water resources in mountain areas globally.

Aeolian dust typically is fine-grained (silt-and clay-sized) material eroded from soil by wind; it can be transported at local, regional, and global scales, with concentration and grain size decreasing with distance (Bullard and Livingstone, 2009). Its mineralogy is usually dominated by quartz and feldspar, with lesser amounts of soluble salts, carbonates, and iron oxides (Loye-Pilot et al., 1986; Reheis et al., 2002). Dust deposition is highly episodic, typically occurring during major wind events in areas downwind from deserts and arid plateaus, such as the Alps, Himalayas, and Rocky Mountains (Laurent et al., 2006; Tanaka and Chiba, 2006; Kavouras et al., 2007). Globally, the largest sources of aeolian dust are in North Africa, the Middle East, and Central Asia (Mahowald et al., 2010). In North America, the largest dust sources are the Great Basin, Colorado Plateau, and Mohave and Sonoran Deserts in the southwestern U.S. and northern Mexico (Prospero et al., 2002; Tanaka and Chiba, 2006; Lawrence and Neff, 2009; Lawrence et al., 2010). Much of this area has sparse vegetation and is arid, receiving less than 120 mm of precipitation annually, and dust is carried predominantly eastward by prevailing winds (Prospero et al., 2002). Most dust is from natural sources, including playas and alluvial deposits (Reheis and Kihl, 1995; Tegen et al., 2004), but soil disturbance on desert, shrub, and grasslands can substantially increase soil erosion from those areas (Belnap and Gillette, 1997, 1998; Neff et al., 2005). Drought can cause increases in dust generation as well, due to its effect on soil moisture and vegetation coverage (Prospero and Lamb, 2003; Munson et al., 2011).

Studies in France, Italy, and Switzerland have documented high pH, Ca^{2+}, and alkalinity concentrations in “red” rain and snow from southerly storms tracking from the Sahara Desert, and the distinctive chemistry has been attributed to aeolian dust entrained by desert winds (Loye-Pilot et al., 1986; Schwikowski et al., 1995; Delmas et al., 1996; Rogora et al., 2004). Similar chemistry in rain and snow in the Rocky Mountains and Tien Shan (Asia) has been attributed to aeolian deposition as well (Williams et al., 1992; Clow and Ingersoll, 1994; Clow et al., 2002; Dong et al., 2009; Rhoades et al., 2010; Brahney et al., 2013). This chemical signature (high pH, Ca^{2+}, and alkalinity) may be explained by partial dissolution of carbonate minerals in dust during transport in the atmosphere or within melting snowpacks (Clow and Ingersoll, 1994; Delmas et al., 1996; Sala et al., 2008; Williams et al., 2009). Dissolution of carbonate dust can have the beneficial effect of neutralizing acid deposition, and in parts of southern Europe, it is estimated to reduce precipitation acidity by more than 50% (Draaijers et al., 1995; Psenner, 1999).

Meteorological and snow monitoring networks provide information required to track the effect of changes in climate on snowpacks. While dust deposition has been investigated through various research programs (e.g., Clow and Ingersoll, 1994; Painter et al., 2012; Landry et al., 2014; Skiles et al., 2015), there are no long-term (eg., >20 years), regional networks for monitoring aeolian dust deposition to snow using standardized methods (Miller et al., 2004; Bullard and Livingstone, 2009). Given the paucity of monitoring data on dust deposition to mountain snowpacks, and observations that dust may impart a distinct chemical signature on snow, we conducted a study to test the hypothesis that the chemistry of precipitation (snow and wet deposition) and aerosols could be used as a surrogate for dust deposition to snow. We then applied the methodology to evaluate spatial patterns and temporal trends in inferred dust deposition in the Rocky Mountains, USA (Rockies) during 1993–2014. The Rockies have experienced significant changes in snowmelt timing over the past several decades (Clow, 2010), as have other mountain ranges that are critical water supplies for arid/semi-arid regions of the northern hemisphere, such as the European Alps (Huss et al., 2009).

In this study, we used data from several long-term monitoring programs that have suitable geographic and temporal coverage for assessing dust deposition to snow in the Rockies. We have conducted annual chemical surveys of the snowpack at approximately 63 sites in the Rockies since 1993; these data cover the snowpack *accumulation* season, which typically is November–March. Dust deposition during the *snowmelt* season (typically April–May/June) was examined using data from the National Atmospheric Deposition Program/National Trends Network (NTN); the NTN has collected weekly composite samples of wet deposition in the U.S. since the late 1970s. Dust deposition to snow that occurs during non-precipitation events (dry deposition) was examined using data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) program, which has monitored aerosol chemistry in the U.S. since the early 1990s. Data from a fourth long-term monitoring network, SNOTEL (SNOw TELemetry), were used to assess changes in *snowmelt timing*. The SNOTEL network is operated by the Natural Resource Conservation Service (NRCS), and provides data on snowpack depth and snow water equivalent (SWE) at approximately 730 sites across the U.S. Data from all four networks were combined in a multivariate statistical analysis to determine the relative influence of climate and dust deposition on snowmelt timing in the Rockies.

The paper is organized as follows: in Section 3.1, we evaluate the utility of using snowpack chemistry as a surrogate for dust deposition to snow. In Section 3.2, spatial patterns and temporal trends in snowpack chemistry across the Rocky Mountains are presented. In Section 3.3, we describe spatial and temporal patterns in wet deposition chemistry. In Section 3.4, trends in aerosol chemistry are presented. In Section 3.5, we analyze the influence of aeolian dust on snowmelt timing, and in Section 3.6, we discuss implications for snowpack water resources.

2. Methods

2.1. Study area

The study area is the Rocky Mountain region of the United States (U.S.), from northern Montana to northern New Mexico (http://co.water.usgs.gov/projects/RM_snowpack/; accessed 5/17/16). The Rocky Mountains form the headwaters for several major rivers in North America, including the Colorado, Rio Grande, and Missouri, which are critical water supplies for arid/semi-arid regions in the western U.S. This study area was selected because of its proximity to aeolian dust sources in the southwestern U.S., and because of

Please cite this article in press as: Clow, D.W., et al., Increasing aeolian dust deposition to snowpacks in the Rocky Mountains inferred from snowpack, wet deposition, and aerosol chemistry, Atmospheric Environment (2016), http://dx.doi.org/10.1016/j.atmosenv.2016.06.076