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The relationships between insoluble precipitation residues, clouds, and precipitation over California's southern Sierra Nevada during winter storms

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HIGHLIGHTS

- Dust and biological residue particles likely INPs found in Yosemite snow.
- Dust more prevalent at higher elevations due to long-range transport.
- Ice clouds present during prevalence of biological and calcium dust residues.
- Dust and biological residues correlated with higher precipitation quantities.

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ABSTRACT

Ice formation in orographic mixed-phase clouds can enhance precipitation and depends on the type of aerosols that serve as ice nucleating particles (INPs). The resulting precipitation from these clouds is a viable source of water, especially for regions such as the California Sierra Nevada. Thus, a better understanding of the sources of INPs that impact orographic clouds is important for assessing water availability in California. This study presents a multi-site, multi-year analysis of single-particle insoluble residues in precipitation samples that likely influenced cloud ice and precipitation formation above Yosemite National Park. Dust and biological particles represented the dominant fraction of the residues (64% on average). Cloud glaciation, determined using satellite observations, not only depended on high cloud tops (>5.9 km) and low temperatures (<−23 °C), but also on the presence of what were likely dust and biological INPs. The greatest prevalence of ice-phase clouds occurred in conjunction with biologically-rich residues and mineral dust rich in calcium, followed by iron and aluminosilicates. Dust and biological particles are known to be efficient INPs, thus these residues likely influenced ice formation in clouds above the sites and subsequent precipitation quantities reaching the surface during events with similar meteorology. The goal of this study is to use precipitation chemistry information to gain a better understanding of the potential sources of INPs in the south-central Sierra Nevada, where cloud-aerosol-precipitation interactions are poorly understood and where mixed-phase orographic clouds represent a key element in the generation of precipitation and thus the water supply in California.

1. Introduction

Mixed-phase clouds, such as those formed orographically, possess combinations of ice crystals and supercooled droplets. These types of clouds are important for precipitation processes,

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such as the seeder-feeder mechanism (Barros and Kuligowski, 1998; Choularton and Perry, 1986; Purdy et al., 2005). Deep and cold orographic cloud systems have been shown to produce precipitation in the ice phase (Coplen et al., 2008), meaning an initial abundance of cloud ice crystals. However, layers of supercooled liquid water have been observed to persist in clouds down to −40 °C (Korolev et al., 2003). For instance, previous work has shown that cold, deep convective clouds can contain liquid water droplets, even down to −37.5 °C and particularly at cloud top (Rauber and Tokay, 1991; Rosenfeld and Woodley, 2000). In order for ice to be present at temperatures above roughly −36 °C, aerosol particles that serve as ice nucleating particles (INPs) are required (DeMott et al., 2010; Murray et al., 2012; Vali et al., 2015). Mineral dust aerosols have been shown to serve as INPs in model simulations, laboratory measurements, and field studies (Atkinson et al., 2013; DeMott et al., 2003; Knopf and Koop, 2006). However, dust INPs efficiency can be contingent upon the specific mineralogy (Hoose et al., 2008) or the extent to which it has been atmospherically processed (Cziczo et al., 2009; Kulkarni et al., 2014; Sullivan et al., 2010a, 2010b). Biological material, either alone as bacteria, fungi, or pollen, or that associated with soil dust, has been shown to serve as the most efficient INPs, forming cloud ice at temperatures as high as −1 °C (Christner et al., 2008; Conen et al., 2011; Morris et al., 2004; O'Sullivan et al., 2014; Pratt et al., 2009). The presence of INPs in mixed-phase clouds has implications not only for ice formation, but also for precipitation originating from these clouds via secondary ice formation and aggregation (Bergeron, 1935; Hosler et al., 1957). However, conflicting results exist regarding the global impact of different sources of INPs on cloud formation (DeMott et al., 2010; Hoose et al., 2008, 2010a), and thus subsequent precipitation formation.

In regions with orographically-enhanced cloud formation such as California's Sierra Nevada (Pandey et al., 1999), ice nucleation is thought to occur (Meyers et al., 1992) and INPs have been shown to become incorporated within the tops of these clouds (Creamean et al., 2013). Thus, precipitation supplying water to the Sierra Nevada and the remainder of California is influenced by both mineral dust and biological INPs, which often originate from long-range transported sources (Ault et al., 2011; Creamean et al., 2013, 2015; VanCuren, 2006). Intensive, multi-agency field campaigns such as CalWater 1 (2009–2011) and CalWater 2 (2015-present) have focused on understanding the role of aerosols during winter storms driven by atmospheric rivers (ARs; narrow, meridional bands of water vapor that extend from the tropics) in California, whereby high altitude *trans*-Pacific aerosol plumes intersect low level plumes of moisture from ARs as they are orographically lifted along the Sierra Barrier (Creamean et al., 2013; Ralph et al., 2015). These winter storms increase snowpack in the Sierra Nevada, which then provides a steady source of water to regional reservoirs during the spring melt season. However, recent impacts from severely reduced snowfall, and subsequent drought in California, provide increased motivation to understand the factors that influence winter precipitation and, thus, improve forecast models and aid the preparation for future cases of severe drought (or flooding). Therefore, observational studies are needed to improve simulations of INPs not only on a global scale, but also on a regional basis as INPs impacts on precipitation can have significant implications for maintenance of water supplies in marginally dry regions.

Although most previous studies concentrated on the northern and central Sierra Nevada, recent studies have shown that mineral dust is frequently transported to the southern Sierra Nevada as well (Axson et al., 2015; Creamean et al., 2014b; Vicars and Sickman, 2011), demonstrating the broad scale implications of long-range transported aerosols on the water budget in California. This is particularly important for the higher elevation southern Sierra Nevada Mountains, which produce deeper ascent with higher cloud tops that should be more capable of extending into the dust layers transported at high-altitudes and impact precipitation formation processes more regularly. The work presented herein focuses on understanding the types of aerosols that affected precipitation at three separate sites in Yosemite National Park in the southern domain of the Sierra Nevada. Previous work has used precipitation chemistry to evaluate the effects of aerosol sources on cloud glaciation in other regions around the globe (Zipori et al., 2015). We build upon previous measurements of insoluble residues found in precipitation samples collected in the northern Sierra Nevada (e.g., Creamean et al., 2015), adding measurements from multiple, high-elevation sites during two subsequent winter seasons (2011 and 2012). We present a more detailed investigation of the chemistry of insoluble precipitation residues as compared to one location in the northern Sierra Nevada in our previous work, with particular focus on dust and biological residues that serve as INPs. Our objectives are to: 1) investigate the detailed chemical composition of precipitation residues in Yosemite and compare with cloud and precipitation properties in the context of storm meteorology, 2) demonstrate the applicability of the methodology to a variety of locations (i.e., not just the site in the northern Sierra Nevada), and 3) provide a spatial and temporal evaluation of residues and their potential influences on cloud ice formation, which subsequently impacts precipitation reaching the surface through mechanisms such as the orographic seeder-feeder process. Results such as those presented here will be useful for assessing the factors that impact water resources in California.

2. Methods

2.1. Sample collection sites

Precipitation samples were collected at three locations in Yosemite National Park from 14 Feb – 16 Mar 2011 and 12 Feb – 29 Mar 2012. The sites, shown in Fig. 1, include Crane Flat (CFT; 1900 m above mean sea level (MSL); 38.11°N, 119.84°W), Badger Pass (BPS; 2200 m MSL; 37.67°N, 119.65°W), and Tuolumne Meadows (TMD;

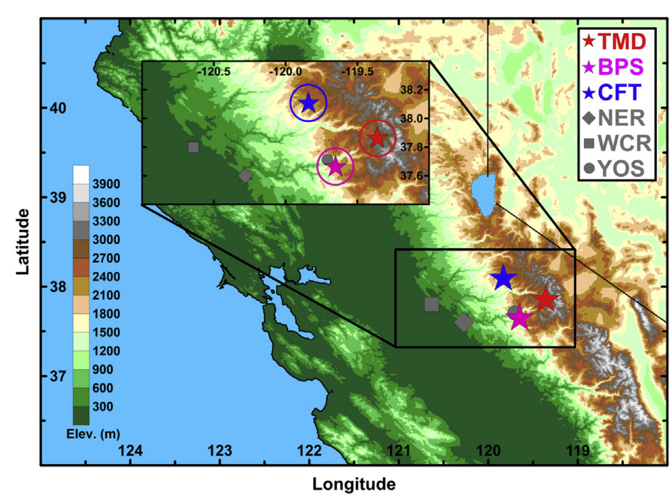

Fig. 1. Map of precipitation collection and meteorological observational sites within the vicinity of Yosemite National Park. Precipitation collection sites include Tuolumne Meadows (TMD), Badger Pass (BPS), and Crane Flat (CFT). Precipitation rate data were acquired from rain gages at the Yosemite Turtleback Dome (YOS) and New Exchequer Dam (NER) sites. Precipitation process estimated by radar was also determined from profiling radar at NER. Integrated water vapor (IWV) data were acquired from Wild Creek (WCR). Inset shows zoomed in surrounding topography, including domains surrounding each site for GOES observations, denoted by the circles.