AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL067978

Hydrometeorological characteristics of rain-on-snow events associated with atmospheric rivers

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Key Points:

- Rain-on-snow (ROS) events are identified in Sierra Nevada watersheds
- Atmospheric rivers (ARs) dramatically increase ROS occurrences
- ARs with and without ROS exhibit distinct differences over land and off shore

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Citation:
Guan, B., D. E. Waliser, F. M. Ralph, E. J. Fetzer, and P. J. Neiman (2016), Hydrometeorological characteristics of rain-on-snow events associated with atmospheric rivers, *Geophys. Res. Lett.*, *43*, 2964–2973, doi:10.1002/2016GL067978.

Received 26 JAN 2016
Accepted 12 FEB 2016
Accepted article online 15 FEB 2016
Published online 29 MAR 2016

Abstract Atmospheric rivers (ARs) are narrow, elongated, synoptic corridors of enhanced water vapor transport that play an important role in regional weather/hydrology. Rain-on-snow (ROS) events during ARs present enhanced flood risks due to the combined effects of rainfall and snowmelt. Focusing on California's Sierra Nevada, the study identifies ROS occurrences and their connection with ARs during the 1998–2014 winters. AR conditions, which occur during 17% of all precipitation events, are associated with 50% of ROS events (25 of 50). Composite analysis shows that compared to ARs without ROS, ARs with ROS are on average warmer by ~2 K, with snow water equivalent loss of ~0.7 cm/d (providing 20% of the combined water available for runoff) and ~50% larger streamflow/precipitation ratios. Atmospheric Infrared Sounder retrievals reveal distinct offshore characteristics of the two types of ARs. The results highlight the potential value of observing these events for snow, rain, and flood prediction.

1. Introduction

Atmospheric rivers (ARs) are narrow, elongated, synoptic corridors of enhanced water vapor transport that play an important role in regional weather and hydrology. Enhanced precipitation may occur when the moisture-laden ARs make landfall and interact with coastal and inland topography [*Ralph et al.*, 2013; *Neiman et al.*, 2013]. ARs deliver beneficial rain and snow to the semiarid western U.S. that form a crucial source of fresh water [*Guan et al.*, 2010; *Dettinger et al.*, 2011; *Rutz and Steenburgh*, 2012]. On the other hand, extreme precipitation associated with ARs can often lead to floods and related damages. *Ralph et al.* [2006] showed that all seven floods during water years (WY) 1998–2006 in the Russian River Basin in Northern California were associated with heavy rainfall produced by ARs. Similarly, *Neiman et al.* [2011] showed that 46 of 48 peak streamflow events during WY1998–2009 in western Washington were associated with ARs.

Compared to other winter storms, AR storms are typically warmer with a higher altitude of the melting level [e.g., *Neiman et al.*, 2008, 2011; *Kim et al.*, 2013; *Warner et al.*, 2012]. Anomalously high melting levels associated with some ARs result in rain (instead of snow) falling at high elevations, thus leading to runoff over a much larger catchment area than during a typical storm. For example, the fractional catchment area contributing to runoff increases from 25% to 100%, as the melting level rises from 800 to 2800 m in the North Fork of the American River, California [*Lundquist et al.*, 2008]. Increased runoff area in turn contributes to larger runoff volume. For example, river forecast model simulations showed that in three California watersheds the runoff volume tripled when the melting level rose by 600 m [*White et al.*, 2002]. A flood-producing rain-on-snow (ROS) AR event in the Bernese Alps, Switzerland, was associated with a 1700 m rise in the melting level altitude within 24 h [*Rössler et al.*, 2014].

Besides larger catchment areas contributing to runoff as a result of higher melting levels, rain falling on existing snow can lead to enhanced runoff due to melting of snow. The flood-producing ROS AR event in the Bernese Alps, Switzerland, mentioned above reduced snow depth by 40–60 cm at three meteorological stations within 6 h [*Rössler et al.*, 2014]. A particularly warm ROS storm (which meets the AR criteria to be described later) in the Pacific Northwest melted 35–100% of the snowpack on the western slope of the northern and central Cascades and contributed to a flood event comparable in magnitude to the record in the Pacific Northwest [*Marks et al.*, 1998].

It should be noted that the melting of snow by the transfer of heat from a liquid drop to frozen snow can be severely limited when the temperature of the drop is only a couple of degrees above freezing. In contrast, the