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Quantifying the role of atmospheric rivers in the interior western United States

Jonathan J. Rutz* and W. James Steenburgh
Department of Atmospheric Sciences, University of Utah, 135 South 1460 East, Rm 819 (WBB), Salt Lake City, UT 84112-0110, USA

**Correspondence to:
J. J. Rutz, Department of Atmospheric Sciences, University of Utah, 135 South 1460 East, Rm 819 (WBB), Salt Lake City, UT 84112-0110, USA.
E-mail: jon.rutz@utah.edu*

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Abstract

Atmospheric rivers (ARs) have increasingly been recognized for their contribution to high-impact weather and climate variability. A recent investigation based on observations located primarily in lowland valleys and basins of the western United States suggests that 10–50% of the total cool season (November to April) precipitation between water years 1998 and 2008 occurred on the day of and day following AR landfall (hereafter the AR fraction), as identified using Special Sensor Microwave Imager data. However, these results are based only on ARs crossing the North American west coast between 32.5 °N and 52.5 °N, which excludes those crossing the west coast of the Baja Peninsula. Here, we identify ARs in the ERA-Interim reanalysis and examine the AR fraction at high-elevation observational sites and in the NOAA/CPC Unified Daily Precipitation Analysis. At high-elevation snowpack telemetry sites, we find good agreement with the AR fraction obtained previously for valley and basin locations. We also show that including ARs crossing the west coast of the Baja Peninsula (as far south as 24°N) substantially increases the AR fraction over the southwestern United States. Copyright © 2012 Royal Meteorological Society

Keywords: **atmospheric river; precipitation; western United States**

1. Introduction

Nearly two decades ago, Newell *et al*. (1992) used the term 'tropospheric river' to describe the filamentary corridors of moisture transport responsible for the majority of midlatitude atmospheric moisture flux. Since then, research has revealed much about the mesoscale structure of these features, now commonly referred to as atmospheric rivers (ARs), as well as their weather and climate impacts. As detailed by Ralph *et al*. (2004), most of the moisture flux associated with ARs takes place in the lower troposphere, along and ahead of cold fronts associated with extratropical cyclones. As such, the movement of extratropical cyclones and their attendant cold fronts largely dictates the behavior of ARs (Bao *et al*., 2006). Further, dramatic precipitation events and life-threatening flooding often occur when these ARs impinge on the high topography of western North America (Ralph *et al*., 2006; Neiman *et al*., 2008a).

Recently, Dettinger *et al*. (2011) used daily precipitation observations from National Weather Service Cooperative Observer Program (COOP) sites across the western United States, which are located primarily in lower elevation valley and basin locations, to assess the percentage of cool season (November to April) precipitation associated with landfalling ARs during water years 1998–2008. Following the methodology of Neiman *et a*. (2008b), they employed Special Sensor Microwave Imager retrievals of integrated water vapor (IWV) from two polar orbiting satellites, each passing over the region twice per day, but somewhat irregularly in space and time, to identify days during which ARs crossed the west coast of North America between 32.5 °N and 52.5 °N. They then calculated the amount of cool season precipitation produced on the day of and day following all AR landfalls, hereafter referred to as the AR fraction.

Their results indicate that ARs contribute a significant fraction of total cool season precipitation at many COOP sites across the western United States (Figure 1). This is especially true near the coast, particularly in north/central California, where the AR fraction approaches 0.50. Inland from the coast, a less uniform pattern is observed – relatively high AR fractions are noted across the interior northwest, while the AR fractions across the interior southwest are very small, if not negligible. However, the southern limit of their analysis does not allow for identification of ARs crossing the west coast of the Baja Peninsula that penetrates into the southwestern United States.

Therefore, the objectives of this study are twofold. First, to determine if the AR fraction at higher elevations is comparable to those found at primarily lower elevation COOP sites by Dettinger *et al*. (2011). Second, to examine if the inclusion of ARs crossing the west coast of the Baja Peninsula increases the AR fraction over the southwestern United States, as synoptic experience suggests.

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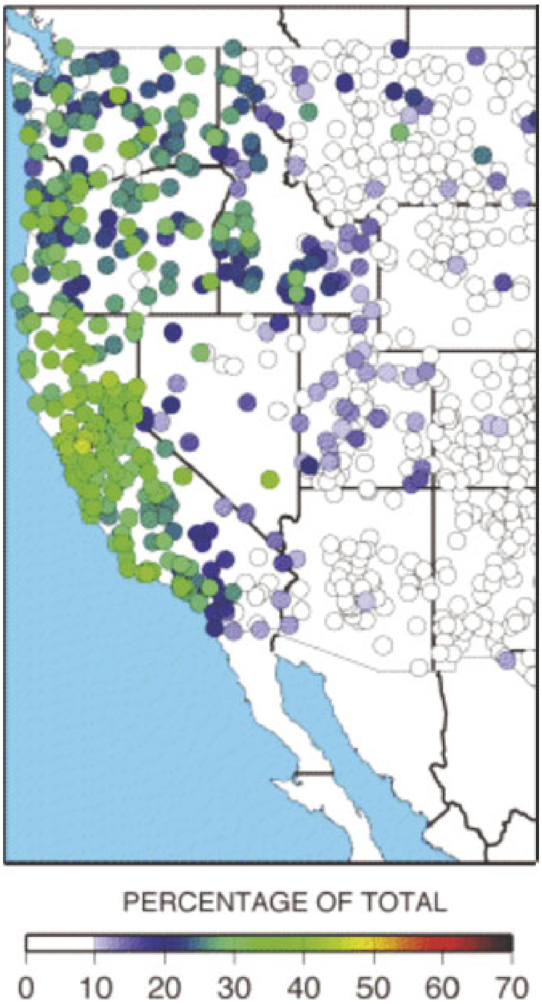

Figure 1. Percentage of total cool season (November to April) precipitation occurring at COOP weather stations the day of and the day following the occurrence of an AR crossing the west coast of North America (32.5 °N–52.5 °N) during water years 1998–2008 (Dettinger *et al.*, 2011).

2. Data and methods

In order to assess the occurrence of ARs at uniform time intervals, we use six-hourly observations of IWV at 1.5° resolution from the ERA-Interim reanalysis (Dee *et al.*, 2011). Ralph *et al.* (2004) show that IWV, which is not dependent on an observed wind profile, is a good proxy for integrated atmospheric water vapor transport. Following the criteria developed and described by Ralph *et al.* (2004), and used in the creation of an AR event catalog by Neiman *et al.* (2008b), an AR is identified as a contiguous region $\geq$2000 km in length and $\leq$1000 km in width containing IWV values $\geq$20 mm. This is done objectively by first locating gridded data points of IWV $\geq$20 mm, and then determining the spatial extent of such contiguous regions following an iterative approach: for each point identified, all neighboring points are then checked and added to the contiguous region if the IWV $\geq$20 mm. Distances between points within this region are then calculated to determine if the dimensional criteria are met. When an AR is identified along the west coast of North America between 24°N and 52.5 °N (compared with 32.5 °N and 52.5 °N as in Dettinger *et al.*, 2011) at all four daily analysis times (00, 06, 12 and 18 UTC), that day is counted as an AR day. The extension to 24°N enables us to include ARs that cross the west coast of the Baja Peninsula and may contribute to precipitation over the southwestern United States.

To examine whether the findings of Dettinger *et al.* (2011) extend to higher elevations, we use the ARs identified in the ERA-Interim reanalysis to determine the AR fraction at snowpack telemetry (SNOTEL) stations, which, using a large storage precipitation gauge, provide automated daily precipitation observations primarily at upper elevations (Hart *et al.*, 2005; USDA-NRCS, 2009; USDA-NRCS, 2010; Rasmussen *et al.*, 2011). We also examine the AR fraction in the NOAA/CPC Unified Daily Precipitation Analysis (hereafter the CPC Analysis), which provides spatially continuous 24-h precipitation analyses at 0.25° grid spacing (Higgins *et al.*, 2000).

3. Results

Qualitatively, the spatial structure of our analysis, based on ARs identified using the ERA-Interim reanalysis, yields results largely consistent with those of Dettinger *et al.* (2011) (cf. Figures 1 and 2). This holds true whether using precipitation data from SNOTEL stations or the CPC Analysis. However, the AR fraction at almost all SNOTEL stations appears somewhat lower than those at adjacent COOP stations (cf. Figures 1 and 2(a)). This may suggest a subtle dependence with elevation of the role of ARs in producing cool season precipitation, and/or bias arising from differences in SNOTEL and COOP gauges and reporting techniques. In the case of the latter, most COOP precipitation observations are manually collected from unshielded 20-cm diameter gauges (NOAA-NWS, 1989; Daly *et al.*, 2007), whereas SNOTEL precipitation observations are automated and collected from 30.5-cm diameter gauges with an Alter shield to help reduce wind effects on catchment and an oil-antifreeze additive to prevent freezing and reduce evaporative losses (Serreze *et al.*, 1999). This could result in differing biases during AR and non-AR precipitation events, which ultimately affects the AR fraction.

AR fractions obtained using the CPC Analysis exhibit a similar spatial pattern to those of the COOP and SNOTEL stations (cf. Figures 1 and 2). This is advantageous in attempting to understand the role of ARs across the western United States, as it suggests that we may be able to use the gridded data to understand the role of ARs in regions where observations are sparse.

Earlier, we expressed concern that the AR fractions obtained by Dettinger *et al.* (2011) over the interior southwestern United States may be underestimated due to a lack of inclusion of ARs crossing the west coast of the Baja Peninsula. Extending the

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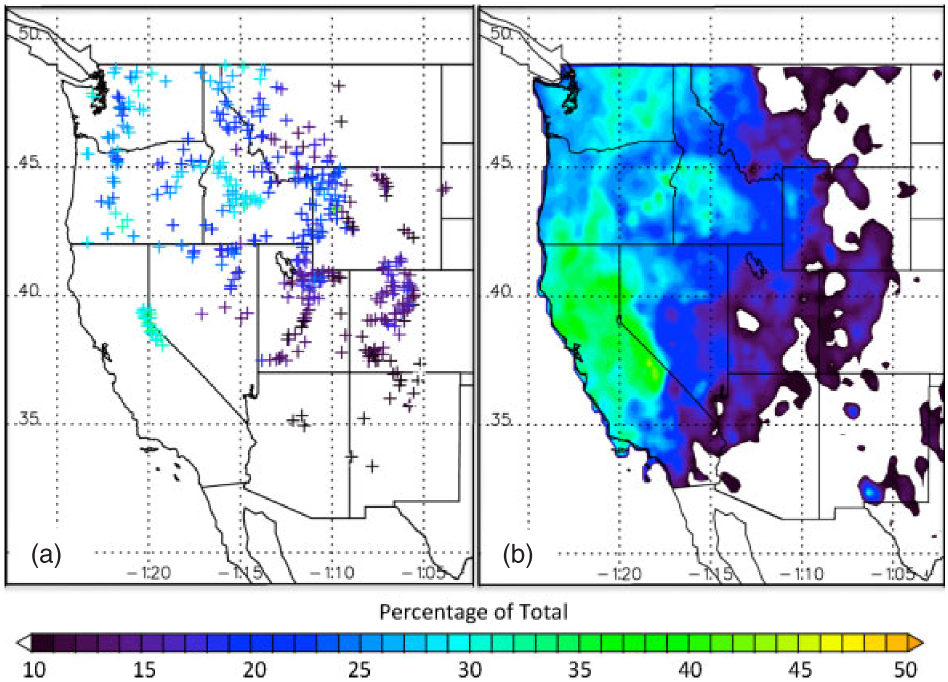

Figure 2. Percentage of total cool season (November to April) precipitation at (a) SNOTEL stations and (b) in the CPC analysis occurring the day of and the day following the occurrence of an AR crossing the west coast of North America (32.5 °N–52.5 °N) during water years 1998–2008.

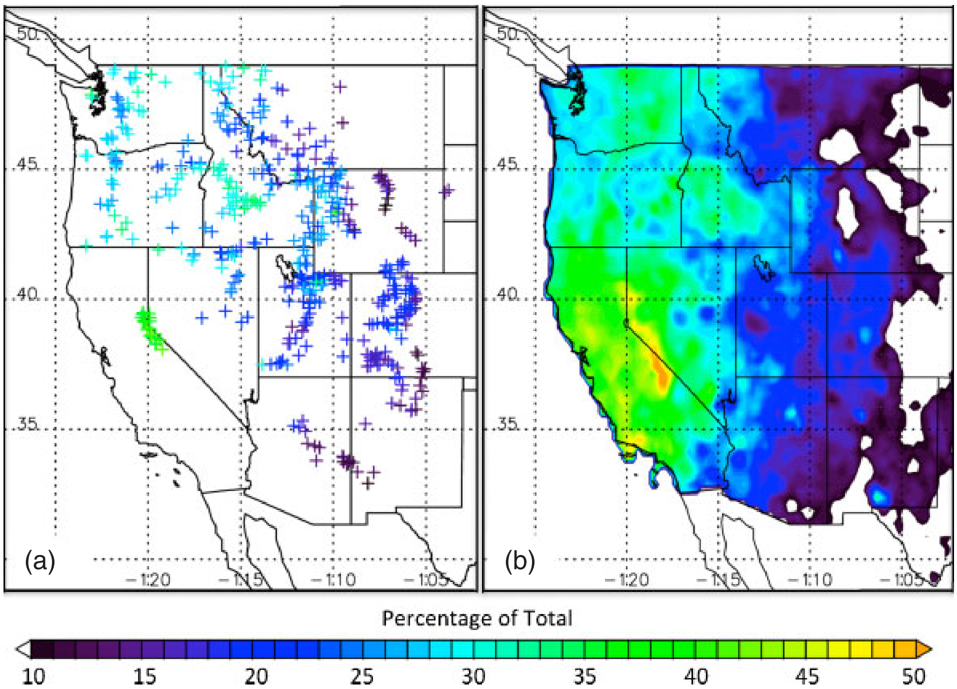

Figure 3. Percentage of total cool season (November to April) precipitation at (a) SNOTEL stations and (b) in the CPC analysis occurring the day of and the day following the occurrence of an AR crossing the west coast of North America, including the west coast of the Baja Peninsula (24.0 °N–52.5 °N) during water years 1998–2008. [Correction added 10 August 2012 after original online publication: in the preceding sentence '(32.5 °N–52.5 °N' was replaced by 'including the west coast of the Baja Peninsula (24.0 °N–52.5 °N)'.].

analysis of landfalling ARs southward from the United States/Mexico border to the southern tip of the Baja Peninsula, we find a substantial increase in AR fraction over the southwestern United States (cf. Figures 2 and 3). Specifically, the AR fraction increases by more than 0.15 in portions of southern California, Nevada, and Arizona (Figure 4(a)), with the percent change in AR fraction largest in Arizona and extreme southwestern New Mexico (Figure 4(b)). The average increase in precipitation on the days of and following AR landfall over all areas where the AR fraction increased by at least 0.15 is approximately 23 mm year^{-1}, which

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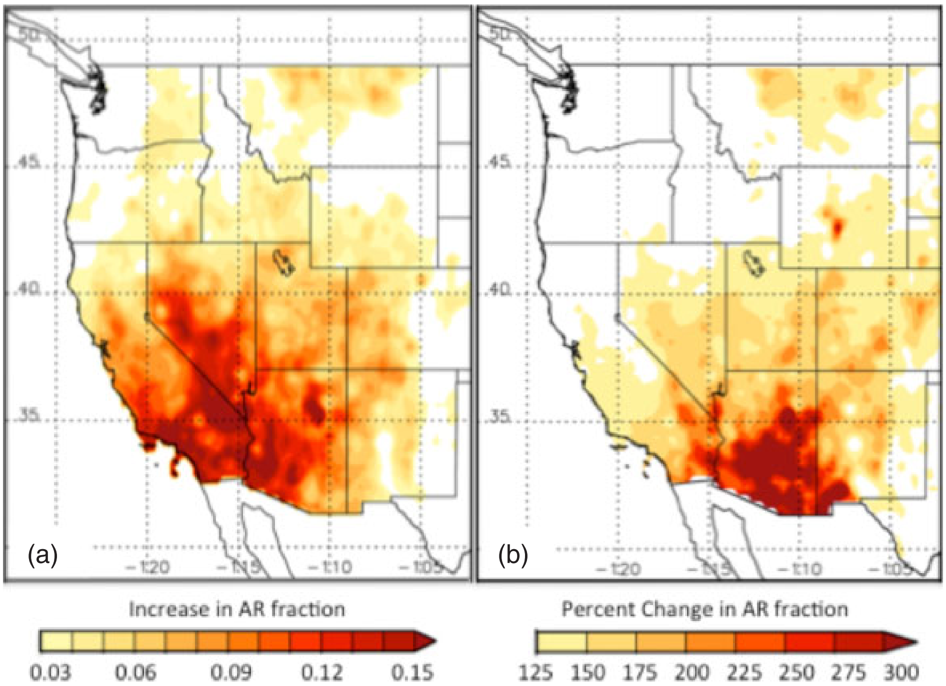

Figure 4. Increase (a) and percent change (b) in AR fraction due to the addition of ARs crossing the west coast of the Baja Peninsula (24.0 °N–32.5 °N).

is substantial in an arid region. These results support the hypothesis that the inclusion of ARs crossing the west coast of the Baja Peninsula leads to substantially higher AR fractions across the interior southwestern United States than indicated in Dettinger *et al*. (2011).

Increases in AR fraction in other areas, such as Montana, are not believed to be the direct result of ARs crossing the west coast of the Baja Peninsula. Because AR precipitation anywhere in the western United States is based solely on the presence of ARs at the coast, some precipitation not directly related to ARs is included in the AR fraction. Therefore, a more likely explanation for the relatively minor increases in some regions is that they are the result of separate, distinct storm systems to the north of landfalling ARs on the west coast of the Baja Peninsula. Differentiating between precipitation falling in the presence of an AR at a specific location and that falling during the occurrence of an AR elsewhere is the subject of ongoing work.

4. Conclusions

The spatial pattern of western United States precipitation derived from landfalling ARs using COOP stations (Dettinger *et al*., 2011) is in good agreement with that shown here using data from the SNOTEL network and the CPC Analysis. Because sites within the SNOTEL network are generally located at higher elevations than COOP stations, this increases our confidence in the overall spatial pattern of AR fraction, and suggests that it is not highly dependent on elevation. We do, however, note an apparent tendency for smaller AR fractions at SNOTEL stations.

We have also shown that including ARs along the west coast of the Baja Peninsula increases the AR fraction by at least 0.15 over much of the southwestern United States compared to the analysis of Dettinger *et al*. (2011), which considered only ARs intersecting the coast between 32.5 °N–52.5 °N. This has important implications for understanding the role ARs play in determining water availability across the southwestern United States.

An underlying issue in the analysis presented here and in Dettinger *et al*. (2011) is that all precipitation over the western United States contributes to the AR fraction whenever an AR intersects the west coast. Given the geographic scales involved, this likely results in some precipitation not being related to the AR being included in the AR fraction, a problem that is likely exacerbated in our analysis by the inclusion of the west coast of the Baja Peninsula. On the other hand, the use of a 2 day time window (the day of and immediately following an AR landfall) likely eliminates some precipitation that may be related to the remnant AR as it moves inland. Future work is needed to deal with these ambiguities and gain a better understanding of the role of ARs in the hydroclimate of the western United States.

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