The 2010/2011 snow season in California's Sierra Nevada: Role of atmospheric rivers and modes of large-scale variability

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[1] The anomalously snowy winter season of 2010/2011 in the Sierra Nevada is analyzed in terms of snow water equivalent (SWE) anomalies and the role of atmospheric rivers (ARs)—narrow channels of enhanced meridional water vapor transport between the tropics and extratropics. Mean April 1 SWE was 0.44 m (56%) above normal averaged over 100 snow sensors. AR occurrence was anomalously high during the period, with 20 AR dates during the season and 14 in the month of December 2010, compared to the mean occurrence of nine dates per season. Fifteen out of the 20 AR dates were associated with the negative phases of the Arctic Oscillation (AO) and the Pacific-North American (PNA) teleconnection pattern. Analysis of all winter ARs in California during water years 1998–2011 indicates more ARs occur during the negative phase of AO and PNA, with the increase between positive and negative phases being ~90% for AO, and ~50% for PNA. The circulation pattern associated with concurrent negative phases of AO and PNA, characterized by cyclonic anomalies centered northwest of California, provides a favorable dynamical condition for ARs. The analysis suggests that the massive Sierra Nevada snowpack during the 2010/2011 winter season is primarily related to anomalously high frequency of ARs favored by the joint phasing of −AO and −PNA, and that a secondary contribution is from increased snow accumulation during these ARs favored by colder air temperatures associated with −AO, −PNA, and La Niña.

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1. Introduction

[2] The 2010/2011 winter season in the Sierra Nevada, California, had a large number of winter storms associated with atmospheric river (AR) landfalls, and a massive April 1 snowpack with near-record levels of snow water equivalent (SWE) at many locations. This happened in a period with large anomalies in the Northern Hemisphere atmosphere, such as large amplitudes of the Arctic Oscillation (AO) and the Pacific North American teleconnection pattern (PNA), as well as strong La Niña conditions with mean sea surface temperature (SST) anomalies in the equatorial central/eastern Pacific (the Niño3.4 region) about three times the practical La Niña threshold of −0.5 K. In the context of the observed [*Kapnick and Hall*, 2010] and projected [*Waliser et al*., 2011, 2012] decline in the Sierra Nevada snowpack, an anomalous winter of this magnitude highlights the need to understand the full range of natural climate variability in the Sierra Nevada in order to better appreciate and convey regional climate projections. Such understanding of regional climate change and natural variability is critical as the Sierra Nevada snowpack provides the main source of water in the area for agriculture, recreation, hydropower, urban supply, and downstream habitats [*Bales et al*., 2006] and strongly influences ecosystem function [*Trujillo et al*., 2012]. Meanwhile, exploration of the possible causes of the natural variability of snowpack, including related meteorological and hydrological extremes, will help to better forecast and manage water resources and floods in California and across the western US.

[3] Our focus on ARs and the Sierra Nevada snowpack stem from their importance to the regional climate, hydrology, and water resources. ARs are narrow channels of enhanced water vapor transport in the atmosphere [*Zhu and Newell*, 1994]. They are responsible for over 90% of the water vapor transport between the tropics and extratropics while occupying less than 10% of the circumference of the earth surface [*Zhu and Newell*, 1998]. The structure of ARs became directly observed and better characterized relatively recently with dedicated field campaigns and improvements in satellite remote sensing [*Ralph et al*., 2004, 2005; *Neiman et al*., 2008a]. A record of historical AR landfalls along the west coast of North America has

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