VOL. 98 • NO. 5 • MAY 2017

EOS

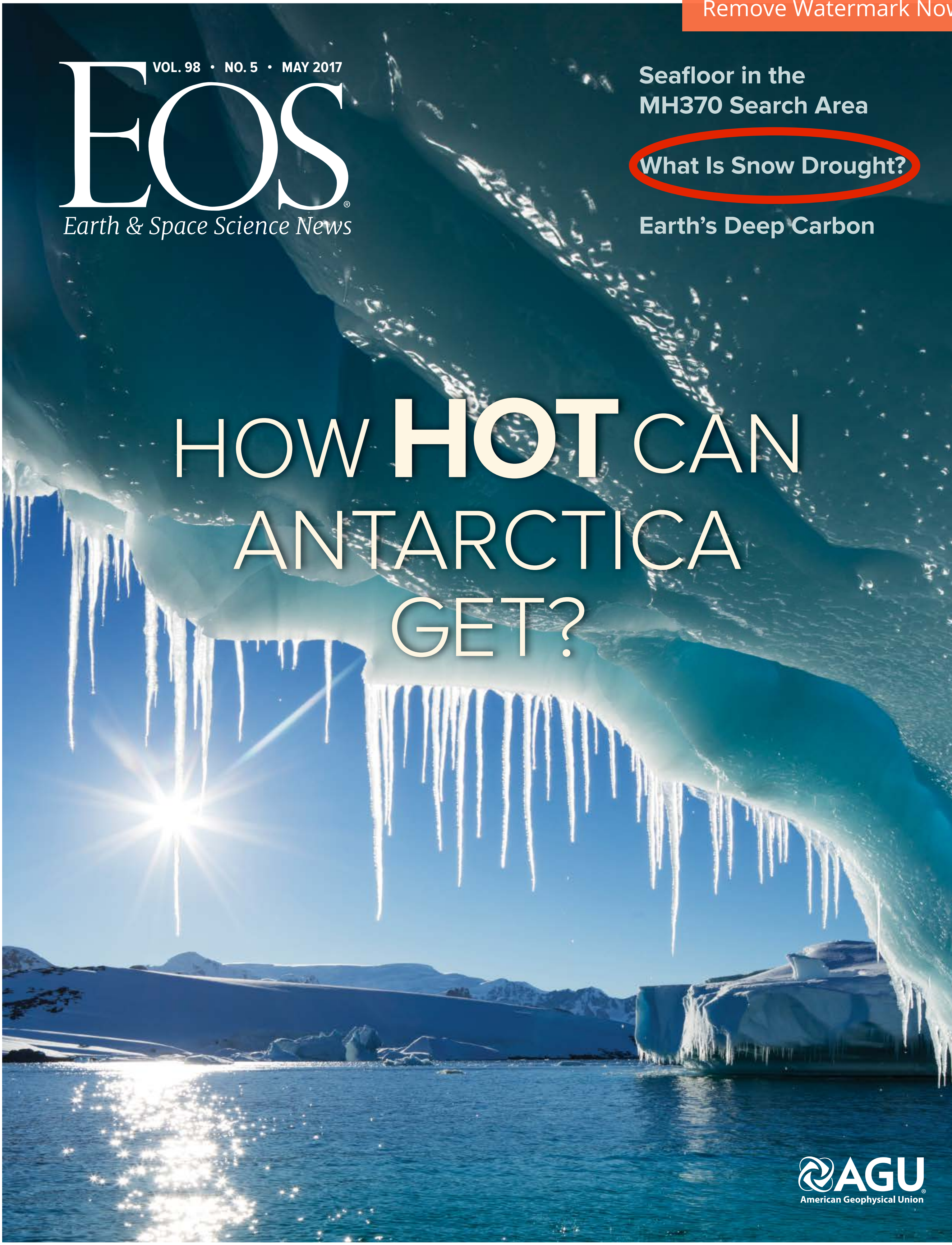
Earth & Space Science News

Seafloor in the MH370 Search Area

What Is Snow Drought?

Earth's Deep Carbon

HOW **HOT** CAN ANTARCTICA GET?



AGU
American Geophysical Union

Defining Snow Drought and Why It Matters

On 12 February, water resource managers at the Oroville Dam in California issued an evacuation warning that forced some 180,000 residents to relocate to higher ground. The story of how conditions got to this point involves several factors, but two clearly stand out: the need to prevent water shortages during a record drought, followed by one of the wettest October–February periods in California history.

The situation in winter 2016 at Oroville Dam highlighted difficulties that many reservoir managers face in managing flood risks while simultaneously storing water to mitigate severe droughts and smaller snowpacks. Central to this difficulty is the idea of "snow drought," a term gaining traction in both scientific and lay literature.

Snow drought refers to the combination of general drought and reduced snow storage. However, among references to snow drought, we observe conditions that reflect a lack of winter precipitation or a lack of snow accumulation during near-normal winter precipitation.

These two uses of the term snow drought have different scientific underpinnings and different implications for water supply forecasting and management. To clarify future uses of this terminology, we propose a new classification to differentiate "dry snow drought," due to lack of precipitation, from "warm snow drought," where temperatures prevent precipitation from accumulating on the landscape as a snowpack.

> We propose a new classification to differentiate "dry snow drought" from "warm snow drought."

Here we use snow conditions during winter 2015 on the West Coast of the United States to illustrate the difference. We also show how snow drought, if not properly incorporated into management decisions, can heighten the potential for emergency situations like the one that unfolded at Oroville Dam.

Subtle Definitions with Important Implications

Drought means different things in different contexts. "Meteorological drought" is defined as a period of below-average precipitation. "Hydrological drought" refers to water storages and fluxes falling below long-term averages.

Then there's "anthropogenic drought," the phenomenon of how most projections of future drought include increases in severity and duration that reflect increasing water demand due to warming [*Diffenbaugh et al.*, 2015]. Add to this the emerging term "snow drought," and you now have a fairly complex picture.

Although meteorological droughts remain difficult to predict in the western United States, widespread declines in snowpack have been observed across the region. These declines, which have been attributed to warming air temperatures and related trends, reflect earlier snowmelt and shifts from snow to rain [e.g., *Hamlet et al.*, 2007; *Harpold et al.*, 2012].

Despite decades of research on changing snowpacks, recent extreme lows in snowpacks have revealed the extent of the unique challenges that snow droughts pose for water managers. For scientists and resource managers to plan for challenges to come, they need to be equipped with solid definitions of all forms of drought, snow drought included.

Winter 2015 on the West Coast: A Tale of Two Snow Droughts

The 2015 winter (from November 2014 through March 2015) highlighted two types of snow drought and their challenges for water management in the westernmost United States. The winter was abnormally warm, with temperatures in the Pacific Northwest (Washington, Oregon, and Idaho) averaging 3.0°C above normal and temperatures in the Sierra Nevada (California and Nevada) averaging 3.4°C above normal.

Winter precipitation, on the other hand, varied considerably from north to south, with the Pacific Northwest receiving 70%–120% of its normal precipitation while the Sierra Nevada received only 40%–80% of normal (Figure 1).

Despite large differences in the amounts and timing of winter precipitation, the snow water equivalent (SWE) in both regions was less than average. On 1 April 2015, snowpack contained between about 50% of the water it usually holds in the Pacific Northwest and a startlingly low 5% in the Sierra Nevada (Figure 1).

These low SWE amounts resulted from two distinct drivers of snow drought. Snow drought in the Pacific Northwest reflected a lack of snow accumulation due to warm tem-

Max Whittaker/Getty Images

A snowboarder threads his way through patches of dirt at Squaw Valley Ski Resort on 21 March 2015 in Olympic Valley, Calif.

peratures that increased rainfall and melted snowpacks, despite near-normal precipitation. Snow drought in the Sierra Nevada also reflected similarly warm temperatures but was enhanced beyond the Pacific Northwest's deficits by the lack of winter precipitation.

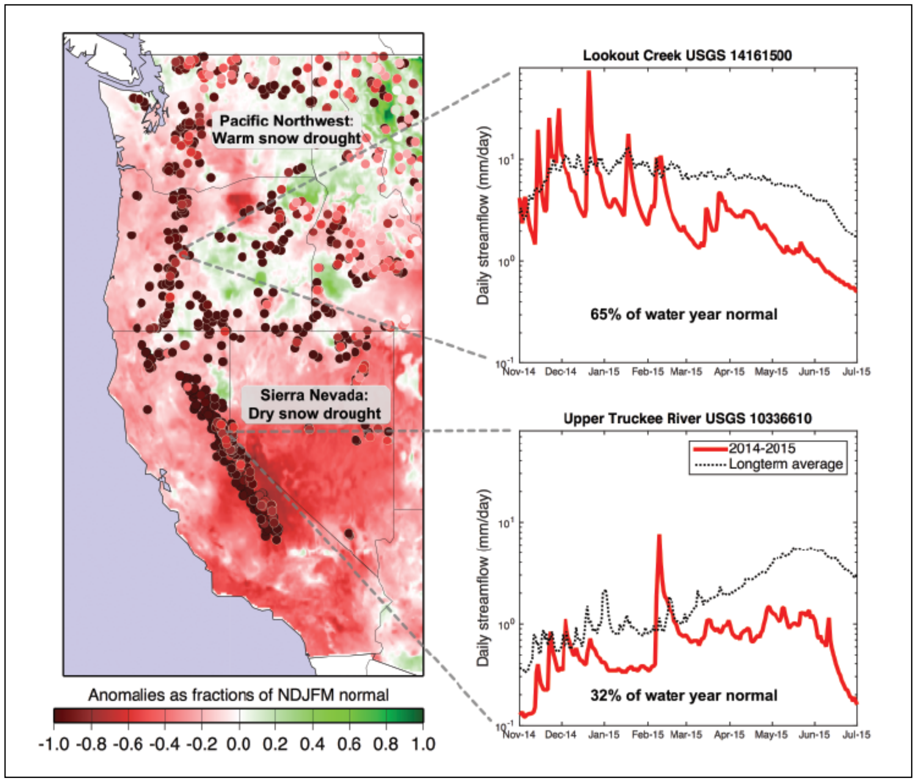
Effects of Winter 2015 on Downstream Water Resources

Streamflow responses to the different snow droughts differed considerably between the regions.

The rainfall that replaced snowfall in the Pacific Northwest yielded large winter peak streamflow events (Figure 1). With most of the water leaving basins in winter rather than during the usual snowmelt season, summer streamflow was far below normal. With less precipitation and warmer temperatures, streamflow in the Sierra Nevada lacked both large winter flows and its usual spring snowmelt pulse and fell to extremely low levels early in the summer.

Streamflow responses generally depend on topography and geology of a given basin but in this case reflect these different snow conditions across both regions. The distinct responses illustrated here have large implications for water management and ecological water availability.

However, the same term, snow drought, was used to describe snow conditions in both regions. A more nuanced definition of snow drought could facilitate discussions of, planning for, and responses to droughts and changing snowpacks.



PRISM, NRCS/CA DWR; USGS

Fig. 1. (left) Precipitation from 1 November 2014 to 31 March 2015 was near normal in the Pacific Northwest and well below normal in the Sierra Nevada (colored map), whereas 1 April 2015 snow water equivalent was below average across the domain (colored dots). (right) These differences in precipitation and snowpack led to starkly different streamflow responses at two characteristic U.S. Geological Survey stream gauges.

Defining and Quantifying Snow Drought

We propose more precise terms to distinguish between the two different snow droughts observed in the Pacific coast states in winter 2015: dry snow drought for precipitation-driven snow drought and warm snow drought for temperature-driven snow lack. Both types of snow drought have SWE that is notably less than normal.

In a warm snow drought, scenarios where SWE is low but precipitation (P) is not (thus a low SWE:P ratio) reflect that a larger than normal amount of precipitation has fallen as rain rather than snow, that an unusual amount of melt has occurred, or both [e.g., *Cooper et al.*, 2016]. If the SWE and precipitation are nearly equal (SWE:P is close to 1) and SWE is below normal, winter precipitation must also be below normal, and the lack of SWE is likely a reflection of low precipitation—a dry snow drought.

The challenge of differentiating dry and warm snow droughts using drought monitoring networks highlights a common weak point: Few drought metrics include storage and release of snow water. For example, the Palmer drought severity index (PDSI) used by the U.S. Drought Monitor treats all precipitation as rain. This simplification means that the PDSI cannot distinguish between warm and dry snow droughts.

Physically based models, such as the North American Land Data Assimilation System (NLDAS) drought monitor, represent accumulating and melting snowpacks, but their results remain spatially coarse and challenging to verify over large areas. Given different effects of warm versus dry snow drought on water-related decision making, drought monitoring needs to better distinguish between the two.

Snow Drought and Water Management

A reservoir manager is faced with balancing the following:

- capturing inflows to reservoirs so that they will still be available for use in the summer
- maintaining enough empty space in reservoirs to capture or ameliorate large flood flows, requiring that large winter flows pass immediately through the reservoirs to maintain extra storage

Snow reservoirs, the water stored in mountain snowpacks, aid both management purposes. Snowpacks are particularly important to western water supplies because they historically persisted into summer when water demand is the highest and prediction of flows is more accurate (being based on snow on the ground rather than on rains to come). The natural reservoirs of water formed by the snowpacks expand the usefulness and reliability of man-made reservoirs by releasing water predictably and closer to times of high demand.

Winter precipitation that falls as rain generates much greater flood risk than when storms deliver snowfall. So most western water management decisions, such as the amount of water to release from a spillway, rely on accurate forecasts of near-term rains and eventual seasonal streamflow amounts, the latter of which depends on the amount of water in the region's "snow reservoirs," which is reduced by snow droughts of either flavor.

In the context of reservoir management, snow drought presents different challenges. During a dry snow drought, streamflows are low, and inflows to reservoirs are reduced all year long. If one knew that such a drought would occur, precipitation and streamflow moving downstream might be captured and stored in dam-impounded reservoirs.

In a warm snow drought, streamflow arrives earlier than normal, but the prospects of a rich spring snowmelt season are limited. Reservoir management is then faced with immediate flood risks followed by subsequent drought conditions.

California and the Case of Oroville Dam

Western water woes are dynamic. To illustrate how quickly fortunes can change, consider the remarkable transition that this past fall and winter brought to California's snowpacks and streamflows after multiple years of drought.

October through December 2016 were very wet months in northern California (with precipitation totals about 170% of normal by 1 January 2017), but because several of the storms were warm rainfall, snowpack in California by 1 January was only 64% of normal (http://bit.ly/snowpacklow). The extra precipitation quickly ran off into impoundments and wetted the landscape. A long string of storms that followed in January and February filled reservoirs, in some cases to the brim.

The early winter snowpack deficits, however, signaled a real possibility that this coming summer might bring a return to drought conditions, as many of the region's reservoirs were still below average following the 2012–2015 drought. So there was a need to impound as much water as possible to provide water during what might be a summer drought.

In the case of Oroville Dam, water managers battled with a reservoir that was beyond capacity but that contained only 46% as much water on the same date in 2015 in the midst of the snow drought described above (and only 30% as much water by September 2015; see http://bit.ly/OroStorage). Not knowing how the winter would play out, California's water managers began storing water during fall rains to buffer against a potential developing snow drought, but instead, they got a record wet winter.

The (Unknown) Hydrological Effects of Snow Drought

The definitions of warm and dry snow drought help to frame science that is fundamental to water management challenges facing snow-dominated regions:

- Which form of snow drought (dry or warm) is likely to dominate in different areas under future climate scenarios?
- How and where can monitoring and management infrastructure be updated to meet the challenges associated with increasing warm or dry snow drought?

Climate models suggest that shifts from mostly dry to increasingly warm snow drought could be a consequence of regional warming [*Pierce and Cayan*, 2013]. However, shifts to warm snow drought are expected to depend unevenly on elevation, moisture sources and transport, and the timing of precipitation.

Thus, retrospective analyses of warm versus dry snow drought are needed to identify areas that have begun to shift from dry to warm (or to warm and dry) snow drought predominance, and networks and sensors for monitoring the full range of snow conditions are critical to better characterizing current and future snow droughts.

We also need better measurements of what phase (rain or snow) is falling during precipitation events. Mixes of rain and snow from place to place, storm to storm, and year to year are almost always inferred indirectly from temperature or changes in SWE [*Rajagopal and Harpold*, 2016]. But direct knowledge could help water managers manage today and plan for the future.

Another monitoring challenge is the scarcity of precipitation and SWE measurement at the highest elevations. Although emerging snow remote sensing methods are suited for filling in gaps in traditional observation systems, expanding ground-based observations of precipitation, SWE, and phase into higher elevations soon will be critical to developing the long-term records needed to define snow drought and its causes over time [*Dettinger*, 2014].

Concerted efforts by scientists, agency-run monitoring networks, water managers, and policy makers will be needed to address the pending prospects of snow drought and how it fits into decision making. For example, what should water managers do to deal with nearly record-breaking snow droughts and flood years in rapid succession? We have only to look to the reservoir behind Oroville Dam over the past 3 years to see these challenges illustrated in dramatic ways.

In response to changing snowpacks and more extreme droughts, we will need a common but nuanced definition of snow drought to facilitate efforts and better manage our water supplies. With such definitions in hand, we may be better equipped to face future water woes in the West.

Adrian Harpold

Students from the University of Nevada, Reno, learn how to measure streamflow at Sagehen Creek Field Station in California's Sierra Nevada during a small rain-on-snow event in March 2016. Winter rain during drought, or warm snow drought, has different management implications than dry winters, or dry snow drought.

References

Cooper, M. G., A. W. Nolin, and M. Safeeq (2016), Testing the recent snow drought as an analog for climate warming sensitivity of Cascades snowpacks, *Environ. Res. Lett., 11*(8), 084009, https://doi.org/10.1088/1748-9326/11/8/084009.

Dettinger, M. (2014), Climate change: Impacts in the third dimension, *Nat. Geosci., 7,* 166–167, https://doi.org/10.1038/ngeo2096.

Diffenbaugh, N. S., D. L. Swain, and D. Touma (2015), Anthropogenic warming has increased drought risk in California, *Proc. Natl. Acad. Sci. U. S. A., 112*(13), 3931–3936, https://doi.org/10.1073/pnas.1422385112.

Hamlet, A. F., P. W. Mote, and M. P. Clark (2007), Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States, *J. Clim., 20*(8), 1468–1486, https://doi.org/10.1175/JCLI4051.1.

Harpold, A., et al. (2012), Changes in snowpack accumulation and ablation in the intermountain west, *Water Resour. Res., 48,* W11501, https://doi.org/10.1029/2012WR011949.

Pierce, D. W., and D. R. Cayan (2013), The uneven response of different snow measures to human-induced climate warming, *J. Clim., 26*(12), 4148–4167, https://doi.org/10.1175/JCLI-D-12-00534.1.

Rajagopal, S., and A. A. Harpold (2016), Testing and improving temperature thresholds for snow and rain prediction in the western United States, *J. Am. Water Resour. Assoc., 52*(5), 1142–1154, https://doi.org/10.1111/1752-1688.12443.

By **Adrian A. Harpold** (email: aharpold@cabnr.unr.edu; @NV_Mtn_Ecohydro), Department of Natural Resources and Environmental Science, University of Nevada, Reno; **Michael Dettinger** (@Mdettinger), National Research Program, U.S. Geological Survey, Carson City, Nev.; and **Seshadri Rajagopal** (@SeshRajagopal), Division of Hydrologic Sciences, Desert Research Institute, Reno, Nev.