Historical and National Perspectives on Extreme West Coast Precipitation Associated with Atmospheric Rivers during December 2010

by F. M. Ralph and M. D. Dettinger

Strong winter storms battered the U.S. West Coast from Western Washington to Southern California in December 2010, producing as much as 250–670 mm (10–26 in. of rain) in mountainous areas (Fig. 1). A common denominator among these events is that the synoptic weather patterns produced a series of strong atmospheric rivers (AR) that transported large amounts of water vapor from over the Pacific Ocean to the U.S. West Coast (Fig. 2). These ARs fueled the heavy rain and flooding, and provided beneficial increases in snowpack. For example, the Southern Sierra snowpack increased from 27% of 1 April normal snowpack on 16 December 2010 to 73% by 22 December—the first full day of winter. The season was well on its way to one of the deepest annual snowpacks ever recorded.

Just how "extreme" were these events relative to other atmospheric river cases in the region? More generally, how does West Coast AR-fed precipitation compare with extreme precipitation in other parts of the United States, such as from landfalling hurricanes and tropical storms? This report uses decades of Cooperative Observer (COOP) daily precipitation reports from more than 5,800 stations across the United States to address these questions and then summarizes the West Coast events and forecasts of December 2010.

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A BRIEF BACKGROUND ON ATMOSPHERIC RIVERS. Atmospheric rivers (AR) are long, narrow zones within extratropical cyclones that contain large quantities of water vapor and strong winds and are responsible for > 90% of all atmospheric water vapor transport in midlatitudes. They are thousands of kilometers long and, on average, only 400 km wide; 75% of the water vapor transport occurs below 2.25-km altitude. ARs produce extreme precipitation in coastal regions because they transport large quantities of

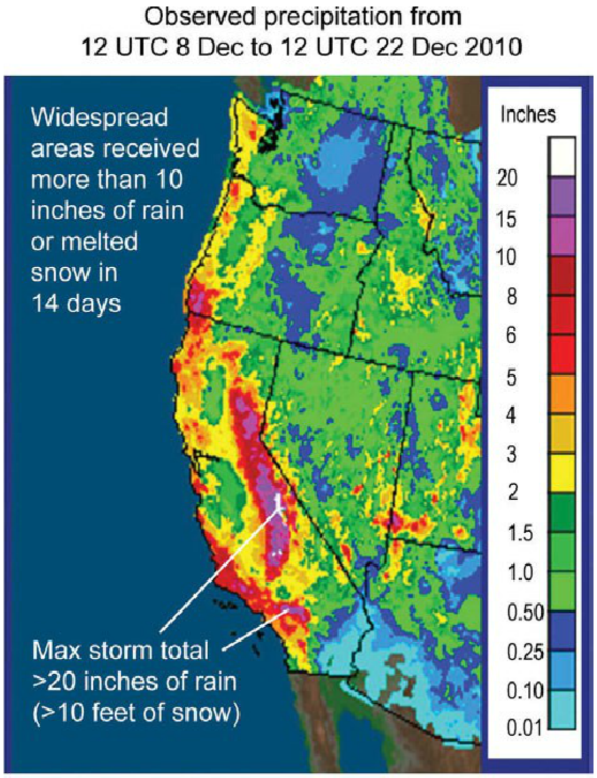

Fig. 1. 14-day observed precipitation in the western United States (courtesy of NWS Advanced Hydrologic Prediction Service).

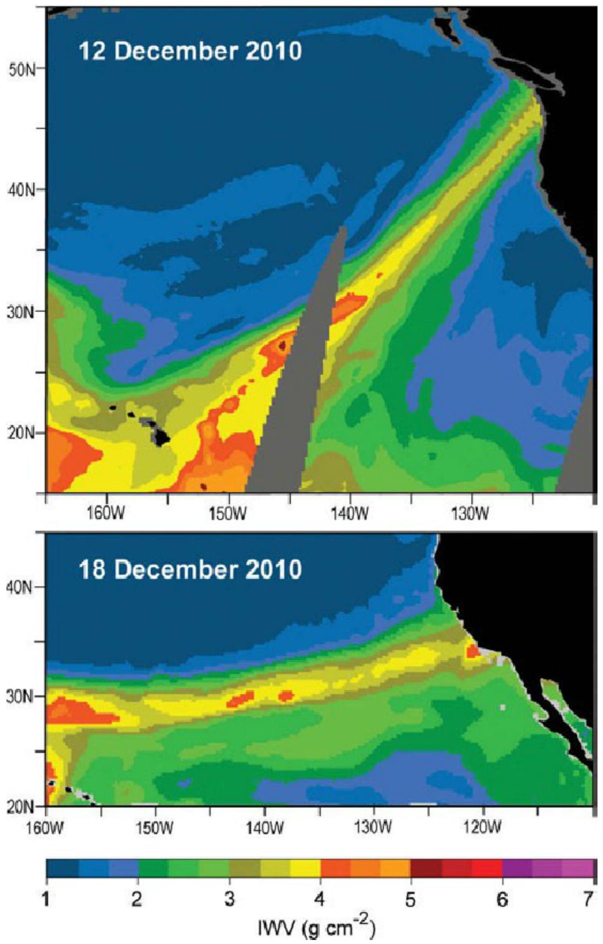

Fig. 2. Polar-orbiting satellite observations of vertically integrated water vapor from SSM/I and SSM/IS showing atmospheric river conditions associated with two of the extreme precipitation events in Dec 2010 on the U.S. West Coast. These images represent two separate and independent ARs (courtesy of G. Wick and D. Jackson).

water vapor and comprise almost ideal conditions for producing heavy orographic rains and flooding when they encounter mountains. Although the dominant precipitation forcing mechanism in the majority of West Coast extreme precipitation events is orographic lifting within landfalling ARs, which are characterized by large water vapor contents, strong low-level winds, and moist neutral stratification, other synoptic-scale and mesoscale processes, such as vertical air motions associated with convection and upper-level jet front systems, can also play a role. The West Coast of North America is particularly vulnerable to ARs, as are the west coasts of other midlatitude continents. Regions other than west coasts can also experience extreme precipitation associated with ARs—as, for example, Moore et al. show in a *Monthly Weather Review* paper about the 2010 flooding in the Nashville, Tennessee, area. Although they are linked to extreme precipitation and flooding, ARs also produce 25%–50% of the annual precipitation on the U.S. West Coast and thus are important in generating water resources in the region.

Documentation of ARs has been enabled by more than 20 years of specialized satellite observations showing total-atmospheric water vapor distributions over the oceans. Figure 2 shows two examples of strong ARs during the active December 2010 period. The first storm produced as much as 292 mm (11.5 in.) of precipitation in Washington over 3 days (10–12 December 2010). The second storm produced up to 670 mm (26.4 in.) in Southern California and 432 mm (17.0 in.) in southern Utah over 6 days centered on 19–20 December 2010. The water vapor distributions shown in Fig. 2 are from passive microwave sensors onboard polar orbiting satellites, which measure vertically integrated water vapor (IWV) [i.e., the total amount of vapor in the atmosphere from the surface to space (g cm^{-2})]. Most of the water vapor is contained in the lower troposphere (roughly 80% of average IWV is contained in the layer below about 700 hPa), which is a layer that was found to be important in earlier extreme precipitation forecasting techniques. While ARs could ideally be identified by observing regions where the wind at 1-km altitude exceeds 12.5 m s^{-1} and IWV exceeds 2 cm with suitable synoptic context, wind data to make this determination are only sparsely available at present. Instead, most ARs are identified by recognizing their largely unique geographic signature as IWV features in SSM/I satellite imagery (i.e., where IWV exceeds 2 cm over areas less than 1,000 km wide and greater than 2,000 km long). [Ralph et al. (2004, 2005a, 2011) used research aircraft data to validate the utility of this pattern in IWV as representative of AR conditions and further demonstrated this using coastal wind profiler data (Ralph et al. 2006, 2011).] For more information on ARs, including a list of publications, see www.esrl.noaa.gov/psd/atmrivers.

ANALYSIS OF EXTREME PRECIPITATION USING COOP DATA. Although much is now known about key geophysical characteristics of ARs, a systematic comparison of extreme AR rainfall on the U.S. West Coast with extreme precipitation elsewhere has not been made. To provide such a comparison, long-term (> 30 yr) COOP precipitation records of 3-day precipitation totals were used to determine where and how

Table 1. Rainfall categories used in this study, and national frequencies of occurrence. Note that an "episode" is defined as a single 3-day period for which one or more stations observed at least 200 mm (~ 8 inches) of precipitation in the same general area.

	Rainfall Category 1	Rainfall Category 2	Rainfall Category 3	Rainfall Category 4
Defining 3-day precipitation thresholds (mm)	$200 \le P < 300$	$300 \le P < 400$	$400 \le P < 500$	$500 \ge P$
Number of stations reaching these 3-day totals per year	173	23	4	2
Number/year of 3-day episodes with station(s) reaching this level	48	9	2	1
Average stations > 200 mm/episode	2	7	13	15

often storms in each of several simple rainfall categories (R-Cats) have been reported across the contiguous United States. The categories used are listed in Table 1.

Methodology. The categories developed and used here were based on daily accumulated precipitation totals reported in the Summary of the Day observations from cooperative weather stations across the United States. Missing data were excluded, as were accumulations from multiple days reported only as multiday totals. While COOP data are quite extensive, their spatial distribution may still miss some areas that could be prone to extreme rainfall, such as remote mountainous locations. While daily totals are a common measure of precipitation, multiday precipitation totals can be of more practical importance with respect to progressive hazards, like floods on main-stem rivers and some landslides. Also, the use of multiday totals reduces potential uncertainties due to the fact that COOP daily rainfall is measured at various times of the day depending upon the volunteer observer.

A "station event" is defined here as an occasion when a single COOP station reports a precipitation total within one of the R-Cats. An "episode" is defined as a 3-day period during which at least one COOP station reports precipitation within one of the R-Cats. A single episode can, and usually does, include multiple station events. Multiple-day precipitation totals are considered because multiday totals are commonly most relevant for landslides, flooding, and other hydrological impacts on main-stem rivers. (Preexisting soil moisture conditions, and whether the precipitation falls as rain versus snow, are also crucial factors. Additionally, shorter-duration, high-intensity rainfall within these 3-day periods is also important for a number of phenomena such as landslides and flooding on smaller watersheds.) Although 2- and 4-day totals were also considered, 3-day windows were used because (a) when 2-day windows were considered, roughly half of the major storms (by 3-day standards) were missed, and (b) when 4-day periods were used, one of the four days typically contributed little to the multiple-day totals (on average, nationally, the driest day of 4-day site-events contributed only 4% of the 4-day totals, whereas, on average across all events, the driest day in a 3-day window still accounts for 10% of the total).

Results. Historical patterns of extreme precipitation, labeled by R-Cats, are shown in Fig. 3. This reveals that, although R-Cat 1–2 events are reported in most states, nearly all R-Cat 3–4 events occurred in California, Texas, or the southeastern states. Thus, extreme-precipitation events in the mountains of California are found to be comparable with the strongest events elsewhere nationally, which occur in the southeastern United States (including Texas). Extreme precipitation events in California are further notable because, unlike those in Texas and the Southeast, several California stations have experienced multiple R-Cat 3–4 episodes during their periods of record. This difference is likely the result of more profound orographic effects in California.

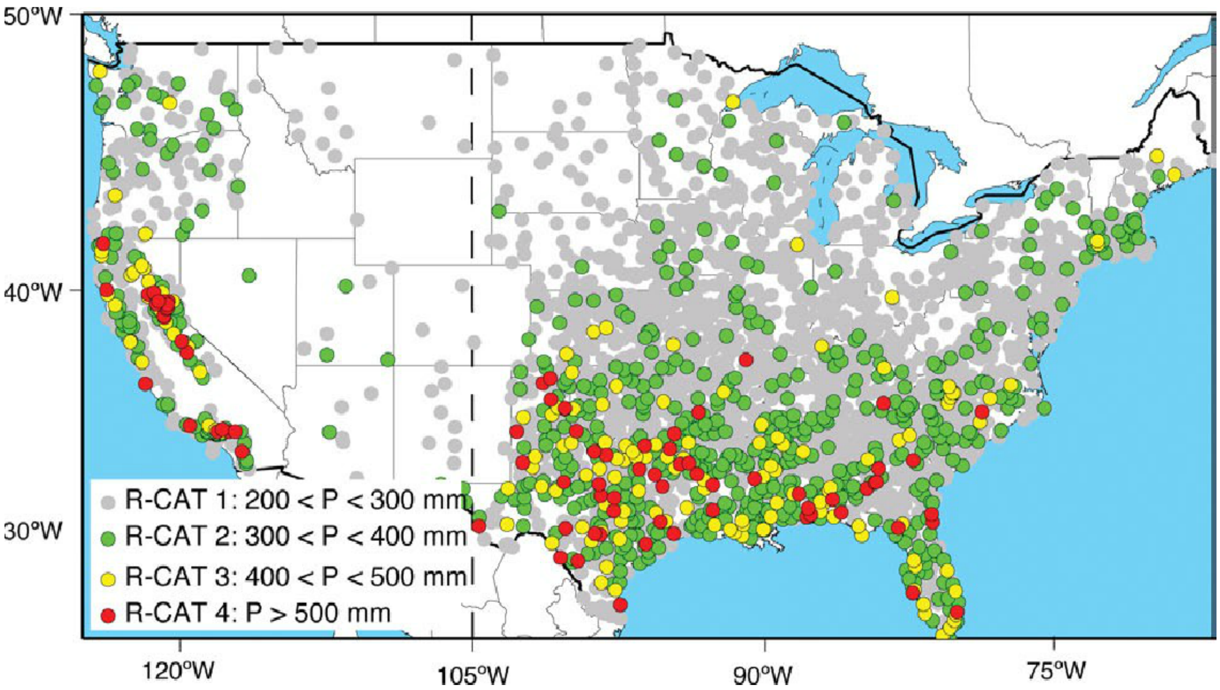

Fig. 3. Maximum 3-day precipitation totals at 5,877 COOP stations in the conterminous United States during 1950–2008. Each site used here had to have at least 30 years of records.

By defining R-Cat "episodes" (i.e., 3-day periods during which at least some stations exceeded a given R-Cat threshold), we verified that the more extreme the episode, the larger its areal extent (Table 1). Episodes were then binned by month-of-year for stations east and west of 105°W. The resulting episode counts (Fig. 4) reveal that most eastern episodes occurred during the spring, summer, and fall seasons, whereas the western episodes occurred almost exclusively during the cool season (November–April), when strong ARs typically impact the region. Despite the timing difference, for a wide range of 3-day precipitation totals the fraction of wet days exceeding those totals are nearly the same for the cool season (November–April) in the western United States as for the warm season (May–October) in the eastern United States (Fig. 5).

Evaluation of all R-Cat episodes from 1997 to 2005 in terms of meteorological conditions showed that in all 17 episodes west of 115°W that met or exceeded the R-Cat 2 threshold, satellite data indicated that an AR had struck the West Coast during the 3-day episode. (115°W is used here, rather than 105°W, because the impacts of ARs are well established in the West Coast states, but not yet farther inland.) During the same period, roughly half of the major eastern events were associated with tropical storms and hurricanes. Other mechanisms important in the East include sequences of mesoscale convective systems (MCS) over the same area. A recent example is the case of the devastating flood of May 2010 in Tennessee that was caused by back-to-back days with slow-moving MCS, which, interestingly, were fueled by a strong AR that had stalled (Moore et al. 2012). On the longer term, by using daily NCEP–NCAR Reanalysis estimates of vertically integrated water vapor transports from 1950 to 2008, it was found that 44 of 48 R-Cat 3–4 episodes in the western United States coincided with landfalling ARs there. Upon normalizing long-term eastern and western counts by number of stations in each region, the annual-averaged frequencies of R-Cat episodes east and west of 105°W are identical (i.e., with 44 R-Cat 1–4 episodes per year). Similarly, the normalized annual-averaged frequencies of R-Cat 3–4 episodes are 2.1–2.2 per year in both areas. Thus, 3-day precipitation extremes associated with landfalling ARs on the U.S. West Coast are heavier than extreme storms anywhere else in the country outside the southeast United States (including those related to landfalling tropical storms and hurricanes). Also, they yield comparable precipitation totals with the southeastern storms, and occur station-by-station just as frequently as the extreme precipitation episodes there.

EXTREME PRECIPITATION STRIKES THE U.S. WEST COAST IN DECEMBER 2010. An example of the extreme nature of the precipitation that can be associated with ARs is described below, along with a synopsis of the associated forecasts. The first major storm in the series produced 292 mm (11.5 in.) of rain at Quinault Ranger Station on the western side of Washington's Olympic Mountains and localized flooding on 10–12 December (even higher storm totals are indicated from other non-COOP sources). Thus, this was an R-Cat 1 event and nearly achieved an R-Cat 2 rating. The second set of storms struck California on 17–22 December 2010, producing more than 670 mm (26.4 in.) of rain in the San Bernardino Mountains of Southern California over those 6 days, and upward of 10–15 feet of snow in the southern Sierra Nevada Mountains. Within this period of heavy rain, the 3-day total at Lytle Creek in Southern California was 440 mm (17.3 in.) on 19–21 December. Thus, it was an R-Cat 3 event. In addition to flooding in Washington and California, the last of this series of storms produced 432 mm (17.0 in.) of rainfall in the mountains of southern Utah over 5 days between 18 December and 23 December at the "Little Grassy" SNOTEL site. The 3-day maximum accumulation at that site was 351 mm (13.8 in.) on 20–22 December, and thus was an R-Cat 2 event. Flooding in southern Utah caused serious property damage and damage to the earthen Trees Branch Dam along the Virgin River near Springdale, Utah. In the case of the Southern California and Utah areas, a strong AR stalled in the region for several days, providing a persistent supply of tropical water vapor from near Hawaii (which also experienced flooding).

As part of NOAA's standard procedures for issuing precipitation and streamflow forecasts, quantitative precipitation forecasts (QPF) were produced in a collaborative effort between the Hydrometeorological Prediction Center (HPC), the Northwest River Forecast Center (NWRFC), the California–Nevada River Forecast Center (CNRFC), and the local NWS Weather Forecast Offices (WFOs) in the region. These QPFs were then transformed into quantitative streamflow forecasts for key watersheds by the CNRFC and NWRFC.

By the time the first storms hit the Washington Coast from 1200 UTC 10 December to 1200 UTC 13 December 2010, QPFs produced by HPC (Fig. 6, top) provided valuable guidance that heavy rain was on its way, and the river hydrographs forecasted by NWRFC gave ample warning for the flooding that ensued. Additional guidance was provided to NWS offices by the NESDIS Satellite Analysis Branch, including many text and graphical products. For example, late on 11 December 2010, the heavy precipitation threat was highlighted: "Both the warm-frontal higher [precipitable water] and frontal boundary moisture plume, or atmospheric river, have a subtropical origin based on latest 5-day blended TPW loop with moisture running near 200% of normal." HPC, NOAA's Environ-

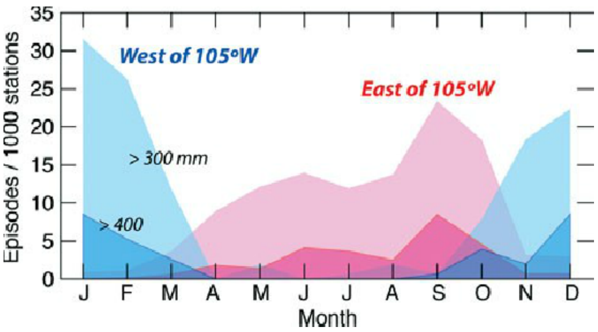

Fig. 4. Seasonality of extreme precipitation events in the eastern versus western United States. Number of 3-day episodes achieving the highest rainfall categories, east (pink) and west (blue) of 105°W, by month of year, normalized to the number of COOP sites in each region. Two thresholds are used: light shading for R-Cat 2 (i.e., >300 mm, or approximately 12 in.), and dark shading for R-Cat 3–4 (i.e., >400 mm, or approximately 16 in.).

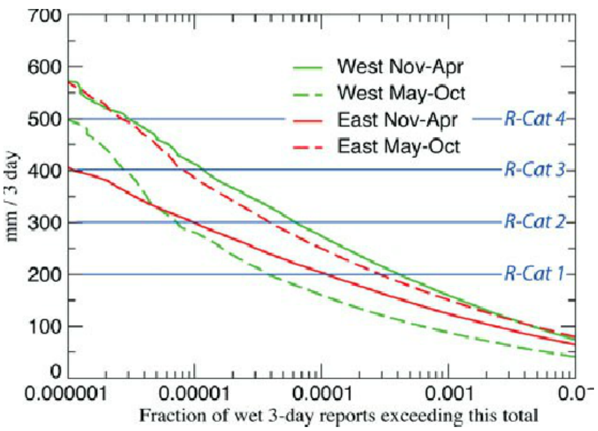

Fig. 5. Frequency of occurrence of 3-day precipitation amounts observed by the COOP network, east and west of 105°W, as the fraction of all 3-day precipitation reports with nonzero totals, accumulated over all stations analyzed in each region, that exceed various totals.

mental Modeling Center (EMC), NWRFC, and the Seattle WFO produced specialized precipitation and hydrologic forecasts for many Western Washington river basins, including the Green River Basin near Seattle, because of the limited flood-prevention capability provided by the damaged Howard A. Hanson Dam. On 17 December, when the next series of powerful storms began to make landfall in central and Southern California, weather forecasters were armed with a similar set of forecasts from HPC, EMC, and CNRFC, including remarkable precipitation forecasts (Fig. 6, middle and bottom) of more than 254 mm (10 in.) in 72 hours for both 17–20 and 20–23 December (1200 UTC–1200 UTC). While these are large QPFs compared to normal forecasts, they are still nearly a factor of two below the maximum observed amounts, partly because they are produced on 32-km-by-32-km grid cells.

It is notable that in the last few years, new tools have been developed, partly through NOAA's Hydrometeorology Testbed (HMT), that help identify and quantify AR conditions and are available to forecasters. These include a product developed at HPC that quantifies the water vapor transport in the form of anomalies from numerical weather prediction models, coastal atmospheric river observatories (ARO) that monitor AR conditions hourly using wind profiler and GPS met data, the AR "flux tool" that displays the ARO observations as well as rapid update mesoscale model output and compares them with thresholds for AR conditions, and a set of real-time "blended total precipitable water vapor" satellite products developed recently by NESDIS and CIRA researchers (www.osdpd.noaa.gov/bTPW).

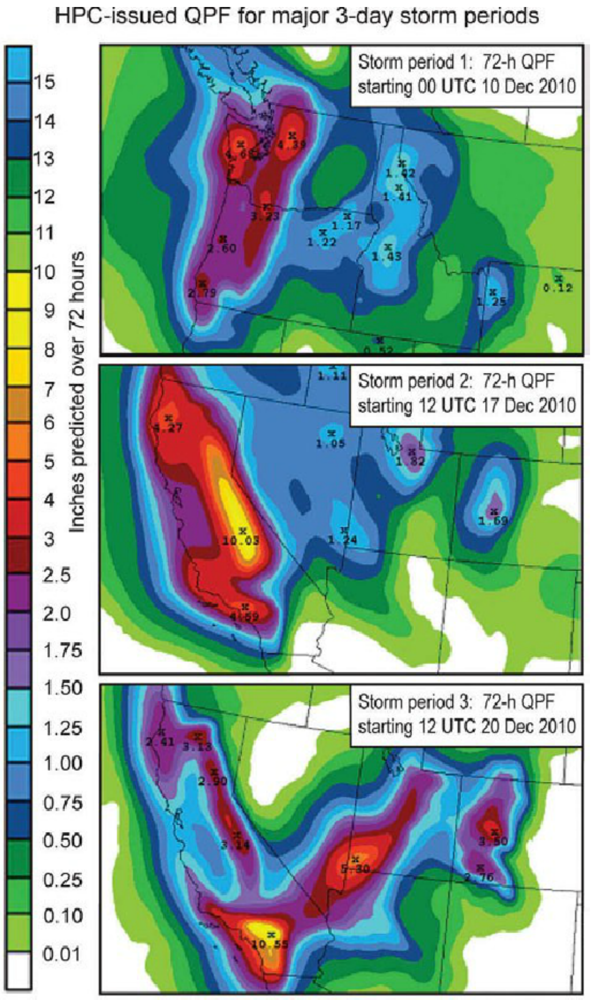

Fig. 6. HPC 3-day precipitation forecasts (in inches). These forecasts were issued at (top) 9 Dec 2010 at 1350 PST for 0000 UTC 10 Dec to 0000 UTC 13 Dec; (middle) 17 Dec 2010 at 0151 PST for 1200 UTC 17 Dec to 1200 UTC 20 Dec; and (bottom) 20 Dec 2010 at 0202 PST for 1200 UTC 20 Dec to 1200 UTC 23 Dec.

IMPLICATIONS. Dave Reynolds, meteorologist-in-charge of the NWS's San Francisco WFO, said NWS operational forecasters were well prepared for the storms in December 2010 in part because of enhanced awareness and improved understanding of the role of ARs. Reynolds has presented online briefings to NWS Western Region staff on the AR phenomenon and related scientific advances. These advances, led by NOAA's Physical Sciences Division (PSD) in Boulder, Colorado, were conducted under NOAA's HMT, and used modern satellite and other observational tools to reveal the importance of ARs to both flooding and water supply in the region. Evaluations of River Forecast Center QPF products by HMT during the cool season of 2005/2006 also revealed that 18 of the 20 most extreme precipitation events that season were associated with ARs. It was also found that QPF was biased low by roughly 50% in the events with greater than 127 mm (5 in.) of precipitation in one day (based on 4-km resolution QPF and QPE). Ongoing research and prototyping is underway to further assess QPF and to explore potential new tools to assist in prediction of extreme precipitation from ARs, as noted in the previous section.

In practical terms, the R-Cat categorization applied here is simple enough to facilitate communication in both technical and public arenas, could be used to standardize research analyses and forecasts, and could improve reporting of climate change projections regarding extreme precipitation. The categorization complements standard return-period methods, straightforwardly accommodating the nonstationarities of climate change and short record lengths that can make estimation of return periods very difficult. Such categorizations will likely be more important as research into the potential impacts of a changing climate on ARs and extreme precipitation begins. The extent to which the R-Cat episodes (from all mechanisms) are identifying truly extreme precipitation episodes may be judged both economically or physically. For example, nationally, six of the R-Cat 3–4 episodes from 1997 to 2005 were associated with damages exceeding $1 billion each. Meanwhile, R-Cat 2–4 episodes (combined) occur historically roughly just as frequently as hurricanes (Atlantic and Eastern Pacific combined, measured by the Safir-Simpson scale) and as violent tornadoes (measured by the Fujita scale). This indicates that the simple R-Cat scale used here is identifying extreme precipitation that is just as rare and extreme, nationally, as are standard categorizations of these other mechanisms of extreme weather. Thus the R-Cat description of the nation's most extreme precipitation episodes could be a useful communications and research tool, and in the present analysis it provided a clear, objective perspective on the severity of precipitation from specific AR storms in the western United States.

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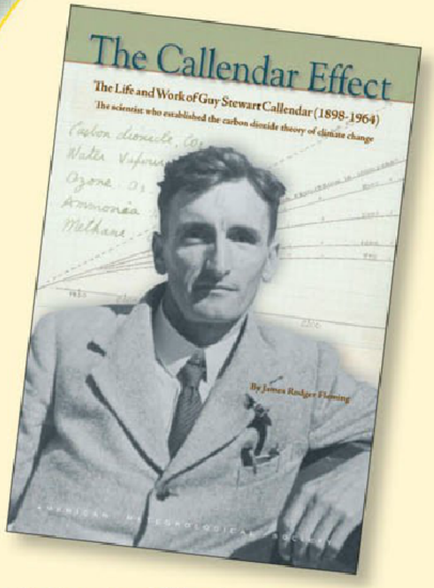

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