Atmospheric Rivers as Drought Busters on the U.S. West Coast

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ABSTRACT

Atmospheric rivers (ARs) have, in recent years, been recognized as the cause of the large majority of major floods in rivers all along the U.S. West Coast and as the source of 30%–50% of all precipitation in the same region. The present study surveys the frequency with which ARs have played a critical role as a common cause of the end of droughts on the West Coast. This question was based on the observation that, in most cases, droughts end abruptly as a result of the arrival of an especially wet month or, more exactly, a few very large storms. This observation is documented using both Palmer Drought Severity Index and 6-month Standardized Precipitation Index measures of drought occurrence for climate divisions across the conterminous United States from 1895 to 2010. When the individual storm sequences that contributed most to the wet months that broke historical West Coast droughts from 1950 to 2010 were evaluated, 33%–74% of droughts were broken by the arrival of landfalling AR storms. In the Pacific Northwest, 60%–74% of all persistent drought endings have been brought about by the arrival of AR storms. In California, about 33%–40% of all persistent drought endings have been brought about by landfalling AR storms, with more localized low pressure systems responsible for many of the remaining drought breaks.

1. Introduction

Drought is a frequently occurring natural hazard that is an important part of the history, life, and resource management activities in the western United States. Drought, broadly speaking, is a protracted period when water availability is deficient to meet the needs for agriculture, forests, rangelands, and other water uses (including urban supplies and aquatic and terrestrial ecosystems). Droughts are a common occurrence in the region but have been more common and severe at times in the prehistoric past and may become more common in the future as the climate warms (e.g., Cayan et al. 2010; Weiss et al. 2012). Among the scientific challenges that droughts pose in the western United States (and elsewhere) are issues of accurately describing their likely future frequencies and intensities, early recognition and forecasting of drought onsets, forecasting of drought durations and endings once a drought is underway, and following and forecasting recovery of affected systems from drought impacts.

Droughts are not just a matter of precipitation deficits; among other things, they also depend on time variations of evaporative demands and water storage by humans or naturally. Nonetheless, droughts in the arid to semiarid western United States are frequently and, in many areas, critically dependent on the arrival (or not) of precipitation (e.g., Hidalgo et al. 2008). The present study is an exploration of long-term historical statistics of the beginnings and endings of persistent droughts across the United States, with an emphasis on the West Coast, and a quantitative evaluation of the historical role of a particular type of storm—the so-called atmospheric river (AR; Zhu and Newell 1998)—in ending droughts, particularly along the U.S. West Coast, during the past six decades. By understanding the role of this storm type in the ending, or ''busting,'' of persistent droughts, greater attention to describing that storm type's frequency of occurrence and in forecasting their arrivals may be motivated. If progress can be made in these areas, drought early warning and planning efforts may be improved with the consequent potential for drought impact reduction.

Atmospheric rivers are constantly moving and evolving pre-cold-frontal pathways of water vapor transport that are thousands of kilometers long but only about 500 km wide and that contain large quantities of water vapor and strong winds (Zhu and Newell 1998; Ralph et al.

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2004; Ralph and Dettinger 2011). They are naturally occurring parts of the global water cycle, responsible for >90% of all atmospheric vapor transport at latitudes of the conterminous United States. When an AR reaches and encounters mountains in the West Coast states, the fast moving, moisture-laden air contained in ARs generally flows up and over the coastal ranges, leading to almost ideal conditions for producing intense and sustained orographic precipitation. Because of the intensity and persistence of their rains, ARs are the cause of many of the most extreme storms along the West Coast (e.g., Ralph and Dettinger 2012; Dettinger and Ingram 2013) and a large majority of the floods in that region (e.g., Ralph et al. 2006; Neiman et al. 2011). In addition to presenting these hazards, ARs also yield important beneficial outcomes, most particularly by providing 30%–50% of annual precipitation and comparable fractions of overall water resources in the region (Guan et al. 2010; Dettinger et al. 2011). West Coast storms, floods, and water supplies are thus intimately linked in most cases by ARs. Atmospheric river storms also are prominent aspects of storm climatologies in other regions globally (e.g., Stohl et al. 2008; Dirmeyer and Kinter 2009; Lavers et al. 2011), so the findings here may have wider applicability.

It is natural to speculate that ARs also may play a special role in West Coast droughts, either by their presence or absence. However, AR storms and storm sequences are short-term (hours to days) meteorological events, whereas droughts are, by their cumulative nature, longer-term phenomena that approach or fall into the realm of climate variations at monthly to multiyear time scales. Thus, identifying explicit connections between ARs and droughts is far from straightforward (especially given the relatively short records of ARs currently available). The present study, therefore, focuses on one element of droughts that has a short-term character that is defined by extreme precipitation events and that operates on time scales comparable to those of ARs: the endings of West Coast droughts. After a discussion of the data and methods used in the study, the extent to which the endings of droughts across the United States are, in fact, abrupt and associated with intense storm periods (like ARs) is investigated. Then, the specific historical role of ARs in busting major droughts in the West Coast states is documented, followed by conclusions and a brief discussion of implications.

2. Data and methods

Droughts impact a wide variety of resources and social sectors and, as a consequence, the occurrence, beginnings, and endings of droughts are measured by a wide variety of indices. No single index describes all manner of droughts, and often the intercomparability of drought indices from place to place can be a concern (Guttman et al. 1992). However, in the present analysis, two of the simpler and more commonly used indices will suffice to give a sense of the beginnings and, especially, the endings (i.e., breaks) of major historical meteorological droughts. These indices suffice because neither time-varying intensities during individual or multiple droughts nor geographical intercomparisons between them are focuses here. Instead, the timing of major drought breaks is the primary focus. It will be shown that these breaks are typically large, unequivocal events that require no great subtlety to detect. Nonetheless, as a check, several different definitions of drought breaks will be evaluated with respect to the broad finding that droughts tend to end abruptly. Also, along the West Coast, drought breaks identified for the AR analysis here will be evaluated in terms of their impacts on the postdrought recoveries of streamflow rates in representative rivers.

In this study, two standard drought indices will be analyzed: the Palmer Drought Severity Index (PDSI) and, to a lesser extent here, the Standardized Precipitation Index for 6-month windows (SPI6). The PDSI attempts to measure the duration and intensity of drought conditions by tracking a combination of temperatures (as a proxy for evaporative demands) and precipitation that is intended to roughly follow the amount of soil water available for plants, runoff, and groundwater recharge—including terms for time variations of water storage and evapotranspiration (Palmer 1965; Alley 1984; Guttman 1991). The SPI6 is based solely on precipitation, which is recast into estimated probabilities of receiving a given amount of precipitation at the location in question in the preceding six months (McKee et al. 1993); broadly, it is the number of standard deviations that precipitation total for the preceding 6 months has deviated from the long-term mean, after the historical precipitation values are mapped into normal distributions. (Standardized precipitation indices are routinely calculated for various windows ranging from the past month to 24 months, but the present analysis addresses only the 6-month window.) Both indices (Guttman 1998) are negative when conditions are drier than normal and positive when conditions are wetter than normal. As conditions become increasingly dry or wet, both indices become more negative or positive, respectively. Drought classifications are based on PDSI and SPI6 according to Table 1.

Monthly values of the PDSI and SPI6 from 1895 to 2011 were obtained for each of 344 climate divisions spanning the conterminous United States from the National Climatic Data Center (NCDC) (http://www1.ncdc.noaa.gov/pub/data/cirs/). In the present study, major

TABLE 1. Standard drought index categories with descriptions for the Palmer drought severity index (PDSI) and standardized precipitation index for 6-month windows (SPI6), positive values correspond to moist/wet and midrange to high values are in italic.

PDSI value	PSDI drought category	SPI6 value	SPI6 drought category
4 and above	*Extremely moist*	*2 and above*	*Extremely wet*
3.00–3.99	*Very moist*	*1.50–1.99*	*Very wet*
2.00–2.99	*Moderately moist*	*1.00–1.49*	*Moderately wet*
−1.99 to *1.99*	*Midrange*	*−0.99* to *0.99*	*Near normal*
−2.99 to −2.00	Moderate drought	−1.49 to −1.00	Moderately dry
−3.99 to −3.00	Severe drought	−1.99 to −1.50	Severely dry
−4.00 and less	Extreme drought	−2.00 and less	Extremely dry

drought endings were defined as occasions when the PDSI or SPI6 crossed the threshold value (PDSI = −2 or SPI6 = −1) separating moderate drought (or moderately dry) or drier values from midrange (or near normal) or wetter values in a given month and then stayed above that threshold value for at least 6 months. These thresholds for identification of drought endings are actually quite arbitrary, but a number of variations will also be explored briefly in the following section. Major drought starts were identified as occasions when the PDSI or SPI6 crossed the same threshold from wetter (more positive indices) to drier conditions (more negative indices) and then stayed below (drier than) the threshold for at least six months.

Next, the extent to which the basic (PDSI based) definition of drought endings actually delineates significant recoveries of hydrometeorological conditions is evaluated briefly by compositing (averaging) streamflows in a representative river from each of five subregions in the West Coast study area in the month before and several months after the identified drought endings, from 1950 to 2009. The gauges from which streamflow composites are shown here are the Snoqualmie River near Snoqualmie [U.S. Geological Survey (USGS) gauge 12144500, 37 m MSL, drainage area 984 km^2] for Washington conditions, the North Santiam River below Boulder Creek (USGS 14178000, 485 m MSL, 567 km^2) for Oregon conditions, Elder Creek near Paskenta (USGS 11379500, 219 m MSL, 242 km^2) for Northern California, Middle Fork Kaweah River near Potwisha (USGS 11206501, 668 m MSL, 268 km^2) for Central California, and Arroyo Seco near Pasadena (USGS 11098000, 426 m MSL, 42 km^2) for Southern California.

When defined this way, the beginnings and endings of droughts can be resolved to within one month, at best. However, because most droughts end abruptly in a single month, conditions within that month can usefully be evaluated to determine the meteorological events that brought the drought to an end. In this investigation, the roles of a few large storms, and specifically atmospheric river storms, as important drought busters were evaluated. The strategy was (i) to use the monthly drought indices to identify those months when major droughts "busted" (ended) and then (ii) to use daily precipitation records during those drought-busting months (as well as months before and after) from representative weather stations in each area to identify the dates of the storms that provided most of the precipitation to end the droughts. Summary of Day (National Weather Service 1989, and updates thereto) daily precipitation total records from long-term, centrally located cooperative weather stations at Seattle–Tacoma International Airport (for Washington State droughts), Oregon State University (for Oregon droughts), Fort Ross (for Northern California: NCDC climate divisions 1 and 2), Fresno (for Central California: NCDC climate divisions 4 and 5), and Los Angeles (for the Southern California coast: NCDC climate division 6) were used to identify the critical days for the ending of droughts from 1950 to 2010; Fig. 2 shows these geographic divisions and locations. These stations are among the longest running stations in each of the West Coast areas evaluated here and tend to be at relatively lower altitudes (where people have lived the longest). This could bias results away from the strongest AR influences because atmospheric rivers are particularly productive of orographic precipitation. However, the PDSI indices that are the basis of the drought-break chronologies used are also based on records from the longest running and generally lower-altitude stations, so the selected stations are believed to be more representative of the drought-breaking conditions for the breaks as identified here. Finally, (iii) the meteorology on the days of the largest precipitation events in each of the drought-ending months was tallied in terms of whether landfalling ARs were the source of the drought-busting storms. The resulting tallies provide a basis for determining the special role of atmospheric rivers as drought busters on the U.S. West Coast.

The meteorology of drought-busting storms was categorized as AR versus non-AR events on the basis of combinations of 1) integrated water vapor content (IWC) fields from the twice-daily Special Sensor Microwave Imager (SSM/I) imagery, available since October 1998, and 2) daily integrated vapor transport (IVT) fields from the NCEP–NCAR 40-Year Reanalysis Project (Kalnay et al. 1996, and updates thereto), available since 1948. The procedure for, and results of, using the recent IWC data to identify West Coast landfalling ARs are described and tabulated in Dettinger et al. (2011), as updates to the compilations developed originally by Neiman et al. (2008). Fundamentally, ARs are recognized (by eye) in IWC data as relatively isolated, continuous, very moist (>2 cm), narrow (<1000 km across), and long (>2000 km) IWC features intersecting the West Coast in a given SSM/I image (Neiman et al. 2008). ARs are recognized (also often by eye) in the longer term, daily NCEP–NCAR reanalysis IVT fields as isolated, continuous, narrow and long corridors of intense (typically $>500\,\mathrm{kg\,m\,s^{-1}}$) IVT intersecting the West Coast. This IVT approach is related to the automated strategy of Dettinger (2004) but was applied here by eye so that a broader range of AR configurations could be recognized than allowed by the automated algorithm in that earlier chronology [Dettinger (2004); see Dettinger et al. (2011) for a discussion of limitations of that automated approach]. During the recent period when both IWC and IVT data are available, both approaches were used to corroborate each other; in the earlier period, only the IVT approach could be applied.

3. How do U.S. droughts begin and end?

Before turning to the question of whether atmospheric rivers play a special role in the endings of West Coast droughts, it is necessary to determine whether, in general, single storms or storm sequences are likely to determine the endings of droughts. That is, do droughts typically begin or end abruptly in a single month, or are the transitions into and out of droughts more gradual, over the course of many months?

Figure 1a illustrates the monthly progress of the PDSI for the South Coast Drainage climate division in California from 1950 through 2011, with 22 representative drought ‘‘breaks’’ indicated by red triangles, based on the PDSI threshold discussed previously. These drought-break months are months when PDSI rises above −2 (from below −2; Table 1) and then stays above −2 for 6 months or more. When the average differences of PDSI in all such drought-break months, from 1895 to 2011, from the PDSI values at various lag and lead times from those break month are computed, the before-and-after relations, indicated by the solid red curve in Fig. 1b, are obtained. The corresponding average drought-break relations for the PDSI series for Washington State are indicated by the solid blue curve in Fig. 1b. These relations show that, on average, for these persisting breaks, the rises during the break months average +3.5 PDSI units in south coastal California and +3.0 in Washington State. For perspective, a rise of +3 PDSI units would typically be interpreted as being enough to indicate a change from, for example, severe drought (−3.5) to normal or mid-range (−0.5) conditions in a single month. Notably, averaged over all breaks, little additional rise or decline of PDSI is indicated in the months following the drought break. Dashed curves in Fig. 1b represent similar calculations except that the restriction that the PDSI remain above −2 for at least 6 months is removed. In this more general case, which includes even the briefest respites from drought conditions, similar average changes in PDSI before and after the drought breaks are indicated, except that the changes in the break months are smaller although still enough to indicate notable moistening in those single months, with the average upward steps being −2.6 PDSI units for south coastal California and −2.2 for Washington State. Results from similar calculations focusing on downward crossings of a PDSI = −2 threshold (the starts of droughts, persistent and otherwise) are shown in Fig. 1c, which indicates a much more gradual and steady decline into droughts than out of droughts (Fig. 1b).

Thus, in Southern California and Washington, droughts typically end in abrupt and significantly wet months (yielding large positive PDSI shifts) but begin more gradually. Calculations similar to those for the month before breaks in Figs. 1b and 1c can be made for 1895–2011 PDSI series from each of 344 climate divisions in the conterminous United States for the beginnings of persistent droughts and for the persisting ends of drought. The resulting average PDSI changes in the month at the beginnings or endings are shown in Figs. 2a and 2b. Notably, average changes in PDSI along the West Coast associated with beginnings and ends of droughts are not substantially different from averages in most of the rest of the conterminous United States. Also, notably, the average one-month steps associated with upward crossing of PDSI = −2 (drought endings) are much larger than those associated with downward crossings (drought beginnings) throughout the conterminous United States (Figs. 2c, 3a).

Although PDSI is a well-known metric of drought, it does not represent all aspects of drought and does not indicate the same levels of drought (for a given PDSI value) in every division (e.g., Steinemann 2003). Therefore, the findings in Figs. 2a–c and 3a were also explored using other thresholds and locally standardized values of PDSI. Upon making these additional comparisons, similar relations (gradual drought beginnings and sudden drought endings) were found to hold for severe-drought beginnings and endings defined as crossings of a PDSI = −3 threshold instead of −2 (Fig. 4a) and for drought

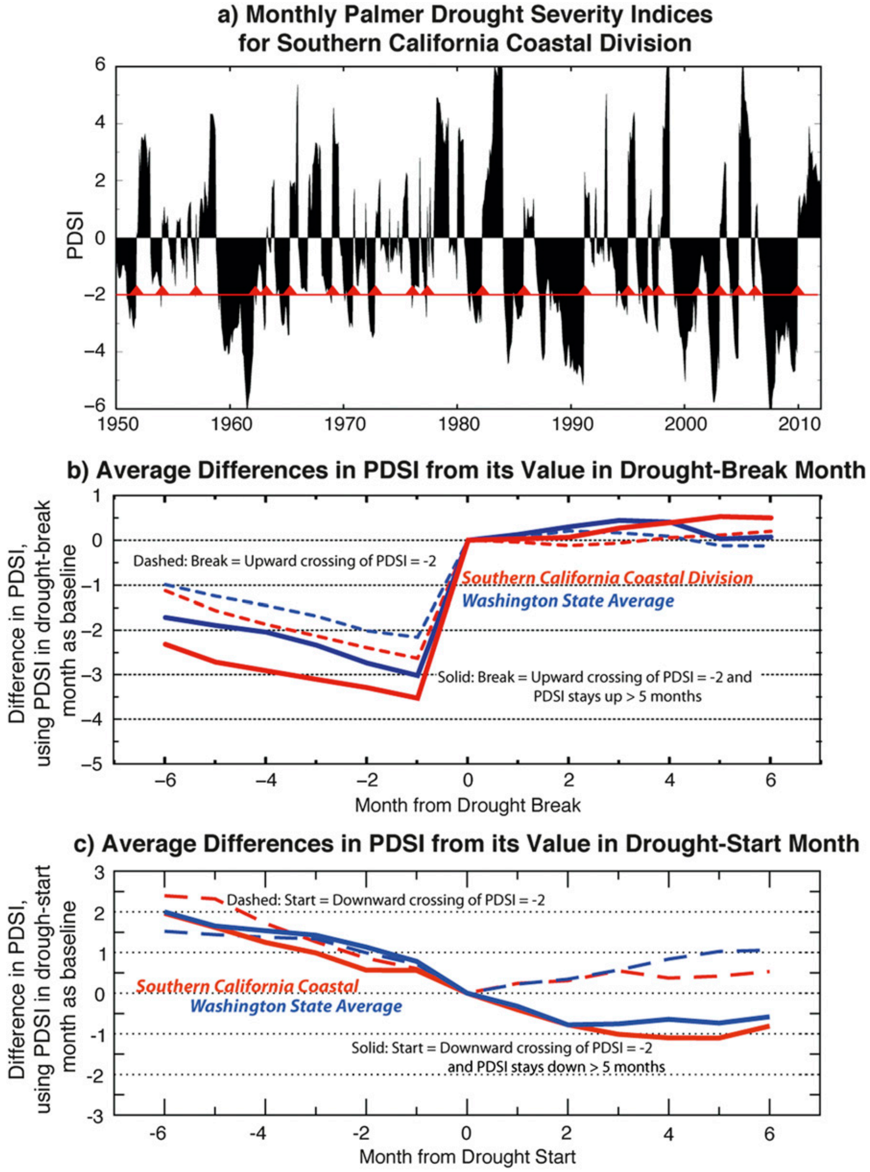

FIG. 1. (a) Monthly PDSI for Southern California coastal climate division; red triangles represent persisting drought breaks as identified by this study. See text for definitions. (b) Long-term average PDSI differences at various lags and leads relative to the drought-break months from the PDSI value in the break months for Washington State (blue) and south coastal California coast (red), with (solid) and without (dashed) a requirement that the PDSI persist in the PDSI > -2 condition for at least five more months. (c) As in (b), but for drought starts.

beginnings and endings measured in PDSI series modified, on a division by division basis, to have their long-term local annual cycles of PDSI removed and variance rescaled to unity (Fig. 4b).

Thus, PDSI-based droughts throughout the conterminous United States begin gradually and end suddenly with a particularly wet month, on average. Recall that PDSI depends on both accumulating precipitation deficits/surpluses and on accumulating temperature (evaporative) demands. Precipitation deficits can only be so large ($<$100% of average) in any given month, whereas precipitation surpluses can be much larger so that precipitation contributions allow PDSI to rise more quickly (in some cases) than it can (ever) fall. Indeed, the average precipitation amount during the drought-ending months is more than one standard deviation greater

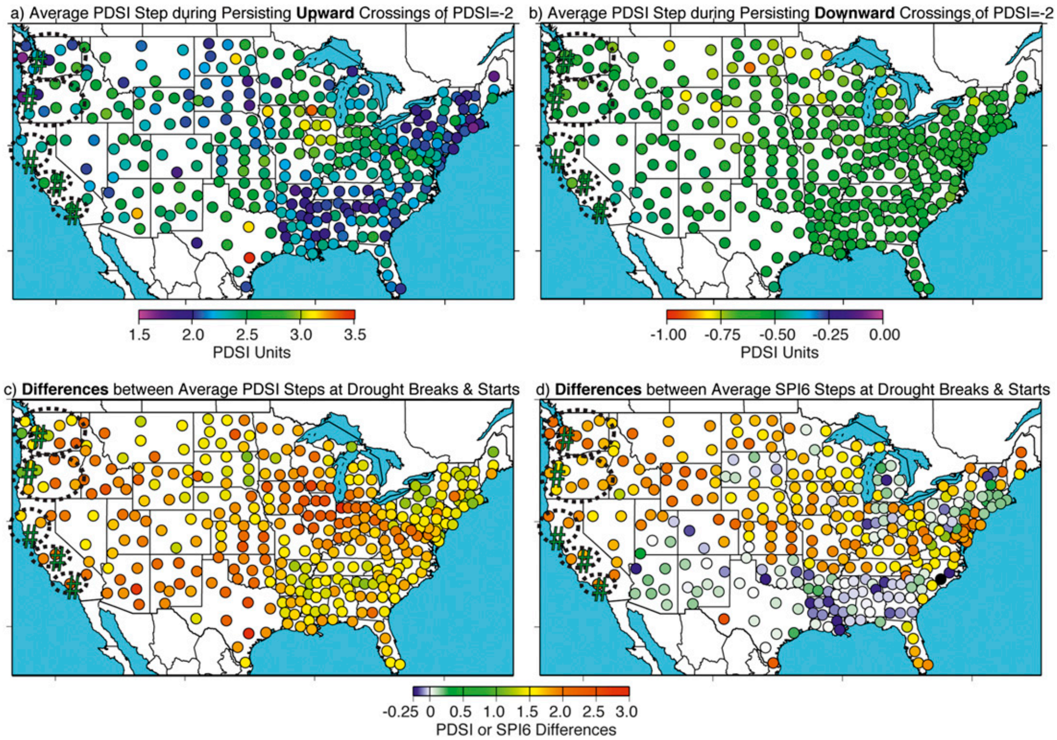

FIG. 2. Average drought index changes (steps) at each of 344 climate divisions during the month when droughts (a) ended and (b) began for the PDSI, 1895–2010, and differences between the average drought index steps during the months when droughts ended and began based on (c) PDSI and (d) the SPI6. Dashed ovals in West Coast states indicate the climate divisions analyzed in later sections; dark green hash signs indicate locations of weather stations used to identify major storm days within drought-break months; see text for location details.

than long-term monthly averages for 97% of the 344 climate divisions (Fig. 4c). The temperature (evaporative) contributions to PDSI are also more restricted than the possible monthly precipitation surpluses encountered in U.S. climates, and temperature anomalies during the drought-breaking months average less than 0.25 standard deviation from the long-term monthly means, except in California (where precipitation and temperatures are correlated in some months) and in the Rocky Mountain and Great Plains regions (where drought breaks are, if anything, associated with cooler-than-normal conditions) (Fig. 4d).

Recalling that SPI6 considers only precipitation, similar calculations have been made based on drought beginnings and endings relative to a threshold of SPI6 = −1. As with PDSI, on the West Coast SPI6-based drought endings involve abrupt SPI6 increases of much greater magnitude than the "steps" at drought beginnings (Fig. 2d). Thus, large one-month precipitation surpluses tend to mark the endings of droughts on the West Coast. Elsewhere, for example, in the humid southeastern United States, the difference between average SPI6 steps at drought beginnings and endings are small and can even reverse their signs, on average, relative to the PDSI-based changes.

Finally, returning to the south coastal California and Washington State series of Fig. 1, the entire distributions, rather than averages, of PDSI steps associated with the persisting beginnings and endings of droughts can be evaluated, as in Figs. 3b and 3c. Clearly, in both of these areas PDSI steps associated with the ending of droughts are, on average, much larger than those at the beginnings of droughts, as in Figs. 1 and 2. In south coastal California, 79% of droughts end in a one-month PDSI step of >2 PDSI units, while no droughts begin with a step that large. In Washington State, 76% of droughts end in steps >2 PDSI units and, again, no droughts begin with steps that large.

To ensure that the primary definition of drought endings used here (centered on sustained upward crossings of the PDSI = −2 threshold) is, indeed, capturing significant ameliorations of drought conditions on the West Coast, streamflows at the five streamflow gauging stations in the West Coast region, listed in section 2, were composited

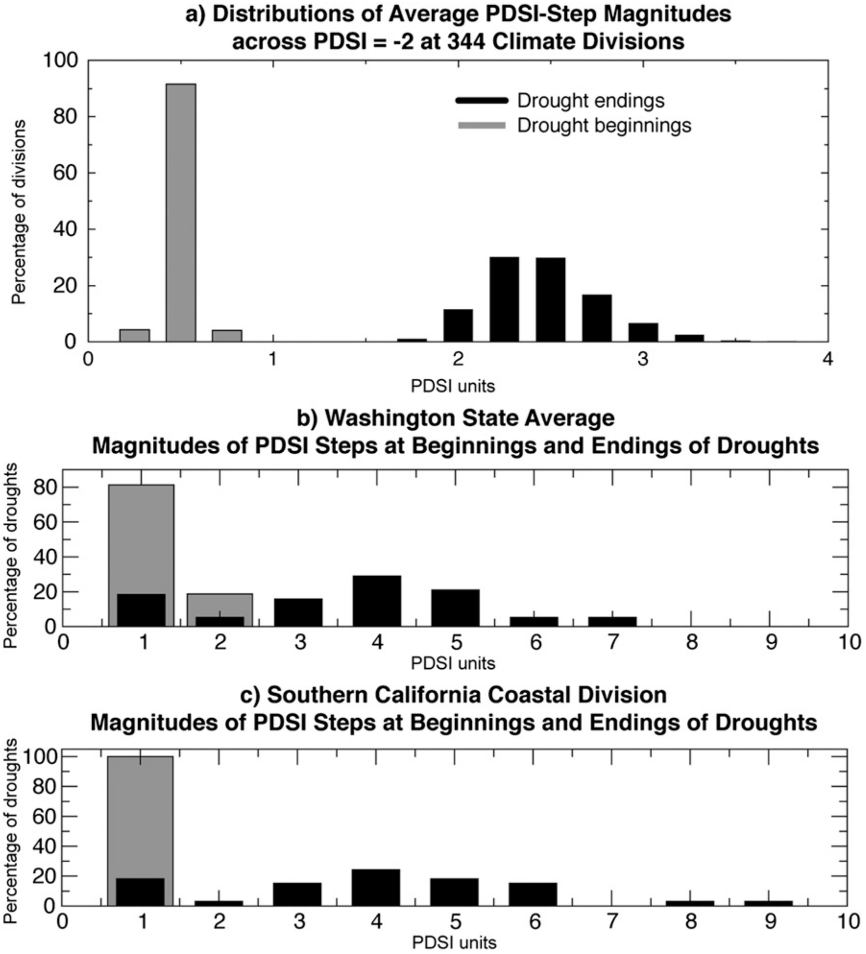

FIG. 3. Distributions of (a) long-term (1895–2010) average magnitudes of PDSI changes (steps) at the beginnings (absolute value of negative steps shown) and endings (positive steps) of droughts at 344 U.S. climate divisions and of all drought beginnings and endings in (b) Washington State and (c) Southern California coastal division. Definitions of drought beginnings and endings provided in text.

for the month before and months following drought endings from 1950 to 2010. The averaged streamflow percentiles before and after the drought endings are shown in Fig. 5 and demonstrate that these drought endings, on average, mark the end of streamflow conditions that are substantially drier than normal and the beginning of near-normal and then wetter-than-normal conditions in each of the five West Coast subregions.

Thus, throughout the conterminous United States, the average PDSI-based drought begins gradually but ends abruptly with a markedly wet month [somewhat in contrast to conclusions by Karl et al. (1987), who used other persistence criteria]. On the West Coast the large majority (>75%) of droughts end abruptly with a very wet month, and all droughts begin (comparatively) gradually. Similarly abrupt drought endings are also experienced on a considerable number of occasions in the eastern United States, notably upon arrival of Atlantic tropical cyclones (Kam et al. 2013).

4. How often do atmospheric rivers end West Coast droughts?

Given the observed abruptness of drought endings, the question of what kinds of storms lead to the persisting endings of West Coast droughts is a sensible avenue for investigation. The approach taken here was to identify the drought-break months for Washington State, Oregon, Northern California, Central California, and south coastal California and then to categorize the storm mechanisms at work during the largest storms in each such month. In particular, the largest storms in the drought-break months—identified from daily precipitation records at representative cooperative weather

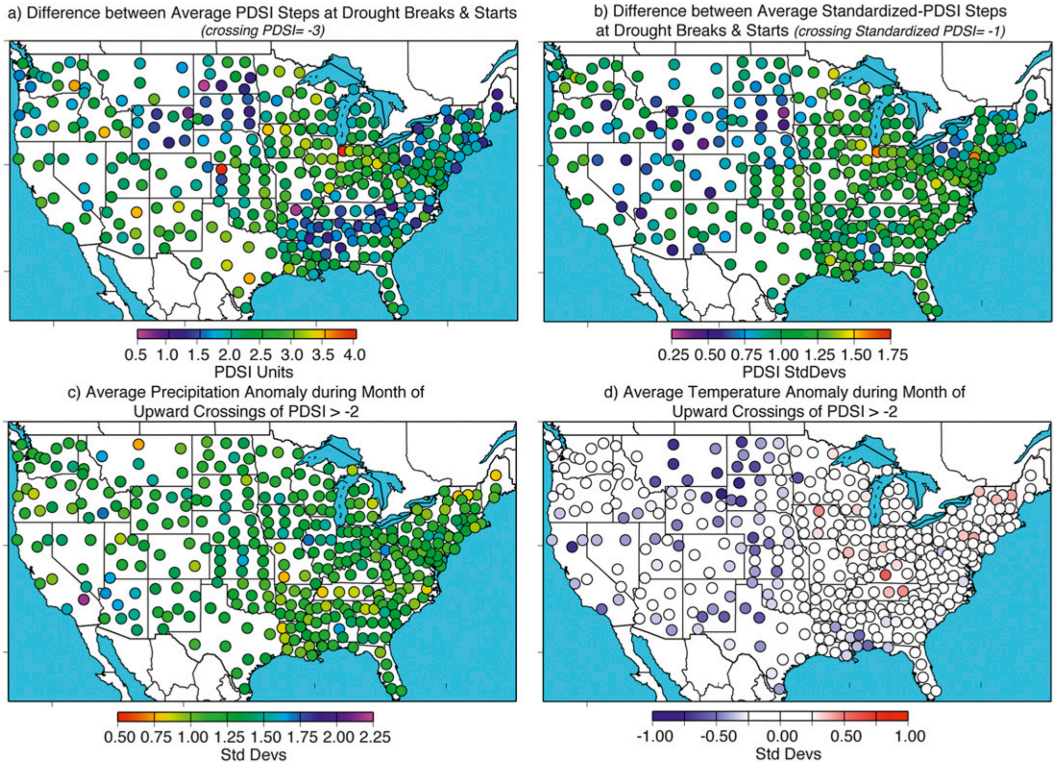

FIG. 4. (a) Differences between (a) the average PDSI steps during the months when droughts ended and began based on crossings of PDSI = −3 and (b) the average anomaly of locally standardized (seasonal cycle removed and rescaled to unit variance) PDSI series during months when droughts ended and began based on crossings of PDSI = −1 std dev. Average (c) precipitation and (d) temperature anomalies during drought endings based on persisting upward crossings at PDSI = −2. All analyses span 1895–2010.

stations in each of these regions—were evaluated in daily integrated water vapor content (IWC) and integrated vapor transport (IVT) fields to determine whether or not they were results of landfalling ARs. Because of limitations on availability of IVT data, this categorization was limited to drought breaks from the 1950–2010 PDSI records.

Notably, in nearly all of the drought-break months identified in these five regions since 1950, one or two very large, often multiday, storms were recorded—storms that stood out from other storms in the month as being large enough to dominate and dictate the unusually large precipitation totals in those months. Therefore, for the purposes of this analysis, in each drought-break month the

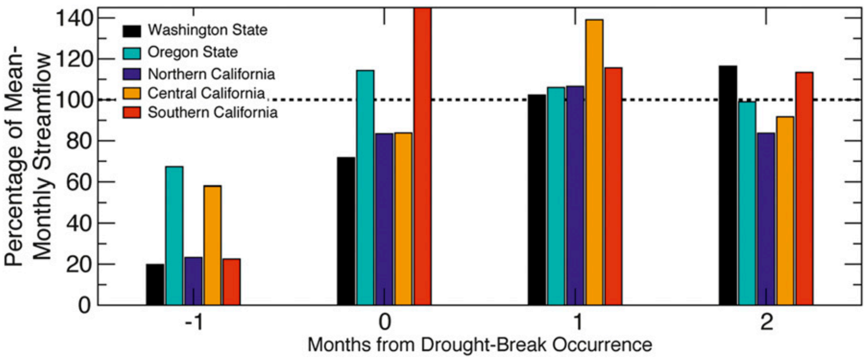

FIG. 5. Average percentages of monthly mean West Coast streamflows (1950–2010) in the month before through two months after drought endings defined by upward crossings of a PDSI = −2 threshold that persist above that threshold for at least 6 months, as in Fig. 2a. Rivers composited are listed in section 2.

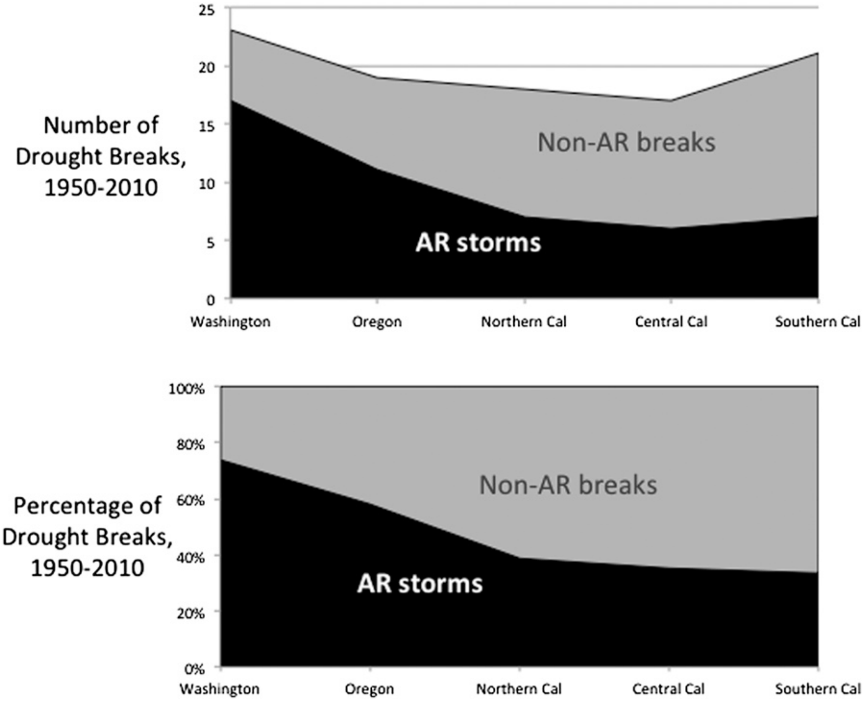

FIG. 6. (a) Number of drought breaks in each West Coast region, total (gray) and due to atmospheric river storms (black), and (b) percentages of drought breaks due to atmospheric rivers (black) and other causes (gray).

storm mechanism associated with the largest storm sequence was assessed (rather than analyzing and compiling the mechanisms from all wet days in every month). The largest storm sequence in a drought-break month was identified as the 3-day string of wet days with the largest precipitation total. In a number of cases, an isolated wet day contributed the largest 3-day precipitation total. On average, these largest storm sequences contributed 48% of the drought-break monthly totals. In many cases, multiple ARs made landfall in a given drought-break month, but only mechanism of the largest sequence was counted in the present analysis.

Upon compiling peak-storm mechanisms for all drought-break months since 1950, the numbers of droughts that were indicated (by this approach) as being broken by a storm fed by a landfalling AR were compiled and are summarized in Figs. 6a and 6b. The number of persisting drought breaks recorded since 1950 along the West Coast declines from a maximum of 23 in Washington to a minimum of 17 in Central California and then rises to 21 in south coastal California (Fig. 6a). The numbers of such drought breaks that are readily associated with landfalling ARs are a maximum in Washington State, where 74% of droughts are broken by landfalling ARs (Fig. 6b), and decline to a minimum in south coastal California, where 33% of droughts are broken by landfalling ARs. Figure 6b shows that the large majority of droughts in the Pacific Northwest (Washington and Oregon) are broken by landfalling ARs, and about 33%–40% of droughts in California are broken thusly. Notably, in the California regions and especially in south coastal California, many of the remaining drought breaks not caused by landfalling ARs were associated with localized low-pressure storm systems (identified here by their telltale closed, or nearly closed, cyclonic whorls of IVT) that often traverse the southern parts of the state from west to east (e.g., Webb and Betancourt 1992).

West Coast drought endings have historically, since 1950, occurred in all months from August to June (Fig. 7). Within this broad drought-breaking season, landfalling ARs have caused droughts to end any time from August to May in the Pacific Northwest, but farther south in California ARs have primarily broken droughts in winter months (November–March). This distribution of AR-fed drought breaks is broadly in keeping with the Neiman et al. (2008, especially their Fig. 2) finding that the Pacific Northwest has a longer AR season than does California. As a result of the longer AR season to the north, ARs can play a crucial role in a much broader seasonal range of drought endings in the Pacific Northwest than in California. Restricting analysis to drought

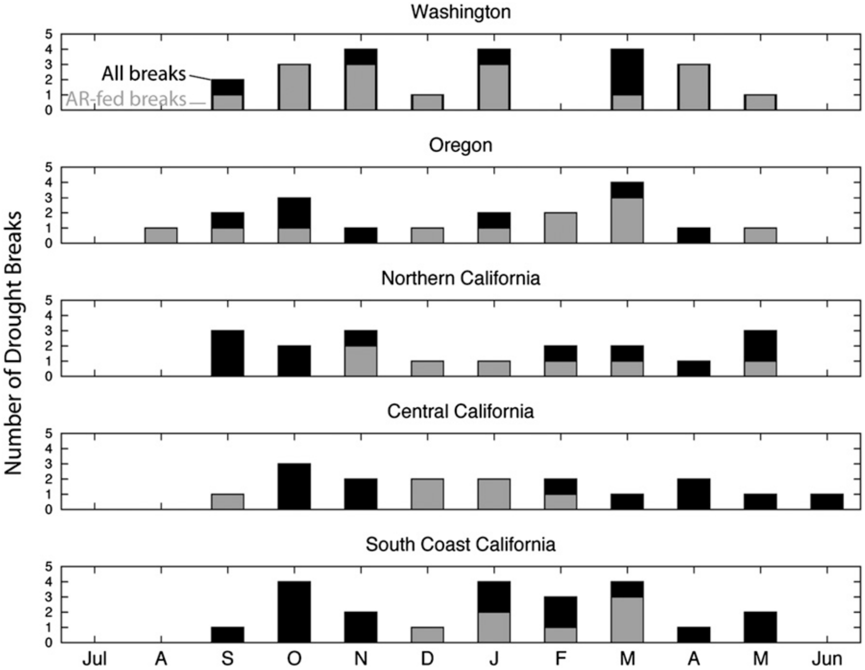

FIG. 7. Seasonalities of major drought breaks, 1950–2010: endings (black bars) and drought endings due to atmospheric rivers (ARs) (gray bars) for five West Coast regions.

breaks that occurred in the climatologically wet October–March season (which is also when atmospheric rivers bring the most rain), the percentages of drought breaks caused by landfalling atmospheric rivers have been 69% in Washington, 64% in Oregon, 60% in Northern California, 45% in Central California, and 47% in Southern California.

5. Conclusions

Atmospheric rivers have, in recent years, been recognized as the cause of a large majority of the major floods in rivers all along the U.S. West Coast (e.g., Ralph et al. 2006; Neiman et al. 2011) and as the source of 30%–50% of all precipitation in the same region (Guan et al. 2010; Dettinger et al. 2011). Even more recently, the important role of ARs in at least some major storms and floods in the interior U. S. West has also been documented (Bernhardt 2006; Rutz and Steenburgh 2012; Neiman et al. 2013). This study presents a straightforward survey of the frequency with which ARs have played critical roles at the other, drier, end of the hydroclimatic spectrum, specifically as sources of the major storms that are the most common causes of the end of droughts on the West Coast.

The approach used was based on the observation that, in most cases, droughts end abruptly as a result of the arrival of an especially wet month (or, more exactly, a few very large storms). This observation is documented using both PDSI and SPI6 measures of drought occurrence for climate divisions across the conterminous United States. Overall, on average, PDSI-based droughts end abruptly with a single very wet month. In contrast, droughts begin more gradually (with an average dryward step in crossing the PDSI drought threshold that is only about one-fifth of the average drought-ending step) as an accumulation of water deficits. SPI-based droughts (which are identified strictly on precipitation records, unlike PDSI, which also incorporates temperature–evaporative fluctuations) along the West Coast end abruptly with a particularly wet month but begin more gradually. Elsewhere in the United States, drought endings in some regions also depend on reduced-temperature (evaporative) effects.

When the individual storm sequences that contributed most to the wet months that broke historical West Coast droughts were evaluated, 33%–74% of droughts were broken by the arrival of landfalling AR storms. In the Pacific Northwest, in particular, a large majority (60%–74%) of all persisting drought endings are brought about by the arrival of AR storms with their copious precipitation. In California, about 33%–40% of all persistent drought endings are brought about by landfalling AR storms, with localized low-pressure storm systems responsible for many of the remaining drought breaks. Of droughts that have ended in the wet October–March seasons (when atmospheric rivers bring most rains), 60%–67% have been broken by landfalling atmospheric rivers in Northern California to Washington and about 45% in Southern and Central California.

Just as West Coast flooding and water resources have been shown to be strongly dependent on ARs by previous studies (e.g., Ralph et al. 2006; Neiman et al. 2011; Dettinger et al. 2011) , West Coast droughts—specifically the endings of West Coast droughts—have been shown here to be intimately linked with the AR phenomenon. This provides one more reason to focus observations and research on improving understanding and forecasts of these vital phenomena, so that drought management and response planning might benefit from better understanding of conditions and occasions that bring the ends to major droughts. Furthermore, initial indications are that West Coast AR arrivals and intensities may change in the warming climate of the twenty-first century (Dettinger 2011), so AR–drought linkages will need to be better understood and incorporated into drought projections if water and land managers are to prepare adequately for the long-term changes to come.

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