AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL074193

Key Points:
- On average, storms in the U.S. West Coast (USWC) and southeast U.S. (SEUS) have the largest precipitation totals in the conterminous U.S.
- Precipitation totals are more strongly correlated with storm duration in the USWC and with storm maximum intensity in the SEUS
- The most extreme USWC storms are most often the most persistent atmospheric rivers rather than high-intensity ones

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Citation:
Lamjiri, M. A., M. D. Dettinger, F. M. Ralph, and B. Guan (2017), Hourly storm characteristics along the U.S. West Coast: Role of atmospheric rivers in extreme precipitation, *Geophys. Res. Lett.*, *44*, doi:10.1002/2017GL074193.

Received 17 MAY 2017
Accepted 17 JUN 2017
Accepted article online 21 JUN 2017

Hourly storm characteristics along the U.S. West Coast: Role of atmospheric rivers in extreme precipitation

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Abstract Gridded hourly precipitation observations over the conterminous U.S., from 1948 to 2002, are analyzed to determine climatological characteristics of storm precipitation totals. Despite generally lower hourly intensities, precipitation totals along the U.S. West Coast (USWC) are comparable to those in southeast U.S. (SEUS). Storm durations, more so than hourly intensities, strongly modulate precipitation-total variability over the USWC, where the correlation coefficients between storm durations and storm totals range from 0.7 to 0.9. Atmospheric rivers (ARs) contribute 30–50% of annual precipitation on the USWC and make such large contributions to extreme storms that 60–100% of the most extreme storms, i.e., storms with precipitation-total return intervals longer than 2 years, are associated with ARs. These extreme storm totals are more strongly tied to storm durations than to storm hourly or average intensities, emphasizing the importance of AR persistence to extreme storms on the USWC.

1. Introduction

Precipitation events (referred to here as "storms") naturally range from weak to strong, and depending on their precipitation totals, intensities, and durations, they can be beneficial and contribute to water resources, be hazardous and result in floods, or yield a combination of impacts. Understanding the conditions that determine where storms are along this spectrum has great practical importance, especially in areas such as northern California where a particular type of storms called atmospheric rivers (ARs) [*American Meteorological Society,* 2017] has been responsible for both replenishing water resources and causing extreme floods [e.g., *Dettinger*, 2016]. During the past few decades many studies have been devoted to investigating different aspects of storms in the U.S., from their diurnal cycles [*Higgins et al.,* 1996; *Nesbitt and Zipser*, 2003; *Dai and Trenberth*, 2004; *Liang et al.,* 2004] and seasonal and multiyear variability [*Cayan and Redmond*, 1994; *Dettinger et al.,* 1998; *Higgins et al.,* 1998, 1999, 2007; *Higgins and Kousky*, 2013] to the frequency of wet days in various regions [*Sun et al.,* 2006; *Dettinger et al.,* 2011]. However, nearly all of these studies have focused on daily to longer time scales of precipitation accumulation, possibly because higher-frequency and temporally and spatially complete rainfall data are uncommon. In this paper, storms defined by continuous sequences of nonzero hourly precipitation are investigated, allowing much finer (temporal) resolution conclusions than from traditional national-scale storm climatologies. Particularly, storm durations and storm intensities and their relationship with storm precipitation totals are evaluated across the conterminous United States (CONUS), with specific focus on the U.S. West Coast (USWC), where precipitation exhibits unusual variability compared to the rest of the CONUS [*Dettinger et al.,* 2011].

One of these unusual characteristics is the dominant role of ARs as determinants of variations in long-term precipitation totals. Landfalling ARs, which are long, narrow plumes of enhanced water vapor transport (IVT) [*Zhu and Newell*, 1998; *Ralph et al.,* 2004; *Dettinger*, 2011] have been shown to be responsible for most major storms and floods in USWC [*Ralph et al.,* 2006; *Neiman et al.,* 2008; *Dettinger et al.,* 2011; *Neiman et al.,* 2011; *Ralph and Dettinger*, 2012; *Ralph et al.,* 2014]. At the same time, ARs provide 30–50% of the annual precipitation in this region [*Guan et al.,* 2010; *Dettinger et al.,* 2011; *Rutz et al.,* 2014]. The connection between landfalling ARs and USWC precipitation has been the focus of many studies; however, at the regional scale, only annual, monthly, and in a few cases, daily precipitation data have been used to investigate this connection. Impacts of ARs at subdaily storm levels have not yet been investigated regionally despite the importance of these time scales to storm impacts [e.g., *Ralph et al.,* 2013]. Using gridded hourly precipitation observations from 1948 to 2002, we explore here the impacts of ARs on duration and intensity of storms and evaluate their contributions to the larger storms with higher potential of causing floods.

Section 2 describes data and methods used in this study. Storm characteristics derived from hourly observations and their relationships across the United States are discussed in section 3. Section 4 then focuses on USWC storms and contribution of ARs to the extreme storms over the USWC. Lastly, a summary of results and conclusions is presented in section 5.

2. Data and Methodology

This study analyzes gridded, hourly U.S. precipitation observations from the NOAA Climate Prediction Center (CPC) (hereafter referred to as CPC precipitation data, https://www.esrl.noaa.gov/psd/data/gridded/data.cpc_hour.html) for the period of 1948 to 2002 [*Higgins et al.,* 1996, 2000]. This data set is derived from hourly precipitation observations at approximately 2500 stations, about one third of which are from National Weather Service (NWS) first-order stations and the rest are from Cooperative Observer Network (COOP) stations. The station data were compiled and quality controlled by the NWS/Techniques Development Laboratory and gridded into 2° latitude by 2.5° longitude grid cells using a modified Cressman scheme [*Higgins et al.,* 1996]. Most stations used to create this data set are located in the USWC states and in the eastern U.S., while western and central U.S. states such as Nevada, Arizona, Utah, and Wyoming contain fewer stations.

Using this hourly data set, storms within each grid cell in CONUS are defined as continuous stretches of precipitation separated by at least 6 h of zero precipitation, with minimal total precipitation of 5 mm during the storm. These criteria were selected to be comparable with previous studies [*Palecki et al.,* 2005], which used minimal 6 h gap between consecutive storms and minimal 2.54 mm of storm total precipitation criteria; however, a range of different criteria (2–48 h of minimal zero precipitation period separating storms and 2.54–15 mm of minimal storm precipitation) was tested to ensure that results are not dependent on the way storms are defined. While the values for storm total precipitation, storm duration, and storm intensities are inevitably different when using different criteria, the overall results remain unchanged.

For each storm, storm total precipitation (mm) is defined as the total rainfall from the beginning to the end of the storm; storm duration (h) is the number of hours with nonzero precipitation (zero-precipitation hours within storm events are not included when computing storm duration) from the start to the end of the storm; mean storm intensity (mm h^{-1}) is storm total precipitation divided by storm duration; and maximum storm intensity (mm h^{-1}) is the largest hourly rate of precipitation observed between the start to the end of the storm. Simple statistics including correlation analysis are performed to better understand storm characteristics.

Guan and Waliser [2015] recently developed a technique to objectively identify ARs globally using 6-hourly fields of IVT in reanalysis data sets based on a combination of AR geometry and IVT intensity thresholds. AR landfall dates along the USWC based on this technique compare well with the AR landfall record developed by *Neiman et al.* [2008] based on manual examination of satellite-observed integrated water vapor (IWV). A record of all landfalling ARs (ARs which intersect the coastline) detected based on applying the *Guan and Waliser* [2015] technique to the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis for the period of 1948–2002 is used here to evaluate characteristics of storms associated with ARs on USWC from 34°N to 48°N. This IVT-based AR record is desirable for this study given the length of record and because IVT is more directly related to precipitation than is IWV [*Neiman et al.,* 2009; *Rutz et al.,* 2014]. The NCEP/NCAR reanalysis has 6-hourly analysis time step. Therefore, in order for the AR chronology data set to correspond with hourly precipitation data set, landfalling AR conditions are assumed to last for at least 6 h centered around the time recorded in the chronology. At each coastal grid cell, if landfalling AR conditions were present at any time from the start to the end of a storm, that storm is considered to be an AR storm, otherwise, it is referred to as a non-AR storm.

3. Storm Characteristics in the CONUS

The total number of storms detected, using the criteria described earlier, between 1948 and 2002 varies from 1600 at grid cells in the western-central U.S. to 6000 at grid cells in the northwestern and southeastern United

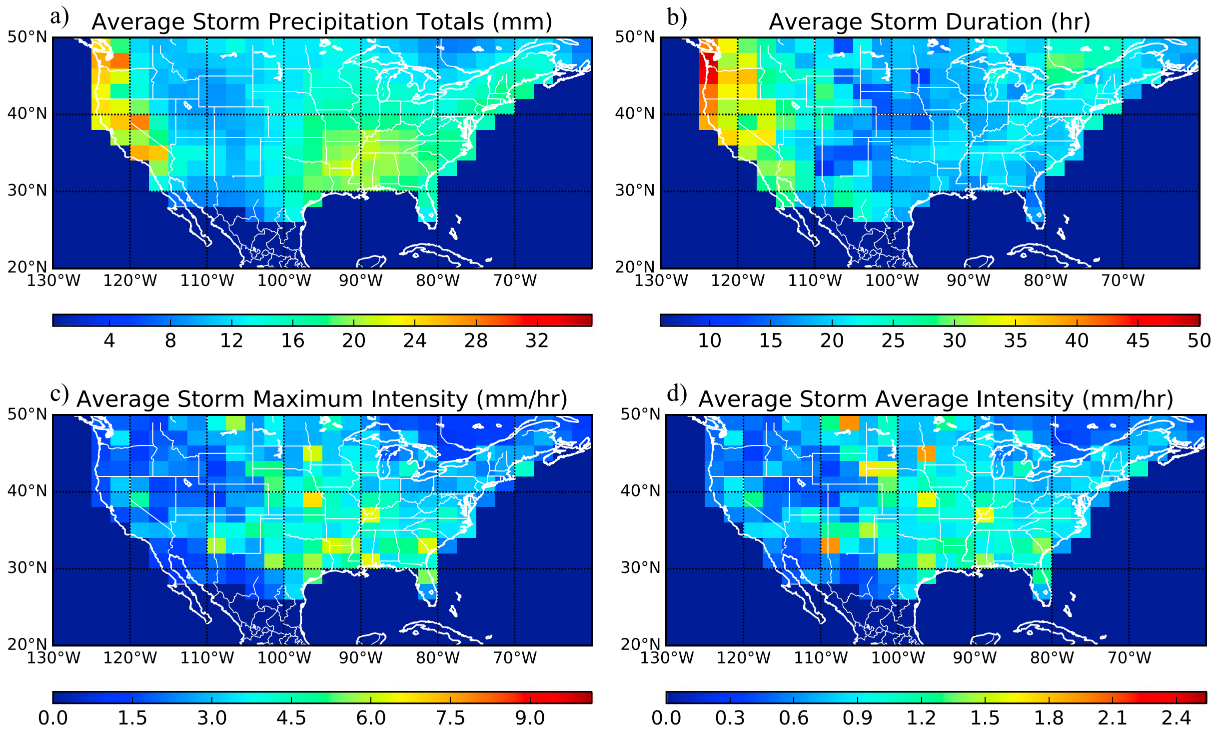

Figure 1. Climatology of (a) storm total precipitation, (b) storm duration, (c) storm maximum intensity, and (d) storm average intensity based on gridded hourly precipitation observations from 1948 to 2002.

States. Figure 1 shows the period of record averages of storm precipitation totals, duration, and average and maximum storm intensities across the CONUS. On average, the USWC and southeast U.S. (SEUS) have the largest average storm precipitation totals, ranging from 23 to 30.5 mm and from 19 to 23 mm, respectively. These regions correspond well to the regions found by *Ralph and Dettinger* [2012] to contain most of the recorded extreme storms with 3 day total precipitation exceeding 40 cm (labeled there as R-Cat 3 and R-Cat 4). Although the hourly data set used here has a coarse spatial resolution, the spatial patterns of the storm characteristics climatology such as duration, intensity, and storm total precipitation are consistent with previous studies which used daily [e.g., *Ralph and Dettinger*, 2012] and 15 min [e.g., *Palecki et al.*, 2005] precipitation records from individual stations across the United States.

While on average both USWC and SEUS have relatively large storm totals, storm characteristics differ between these two regions. The average duration of USWC storms is about 30–50 h, longer than the average SEUS durations of 15–25 h (Figure 1b). On the other hand, the average maximum (and average) storm intensity in SEUS ranges from 3.5 to 7 (0.7 to 1.7) mm h^{-1}, notably higher than in USWC where the average maximum (and average) intensities are about 1.5–3 (0.6–1) mm h^{-1} (Figures 1c and 1d). These different storm characteristics reflect dominant storm mechanisms in the regions. In SEUS, convective precipitation is the major contributor to the storms, leading to short but intense precipitation, whereas in USWC, ARs, and stratiform precipitation are dominant sources of precipitation resulting in longer storms with relatively lower intensities.

For applications such as reservoir management and flood risk mitigation, it is extremely important to understand which storms will contribute the largest amounts of precipitation in a region. As shown in Figure 2, storm total precipitation is more strongly correlated with storm duration than with storm maximum intensity in many parts of CONUS, especially on USWC where Pearson correlation coefficients between storm total precipitation and duration are from 0.7 to 0.9. These findings are consistent with results presented in *Brommer et al.* [2007], stating that coastal areas of northern California and regions within the Gulf States are more likely influenced by storms with long duration than other parts of CONUS. The correlation between storm total precipitation and maximum storm intensity is comparable between USWC and SEUS with correlation coefficients ranging from 0.5 to 0.65. Storm total precipitation has rather weak correlation with storm average intensity than with storm duration and maximum intensity across the CONUS (Figure 2c).

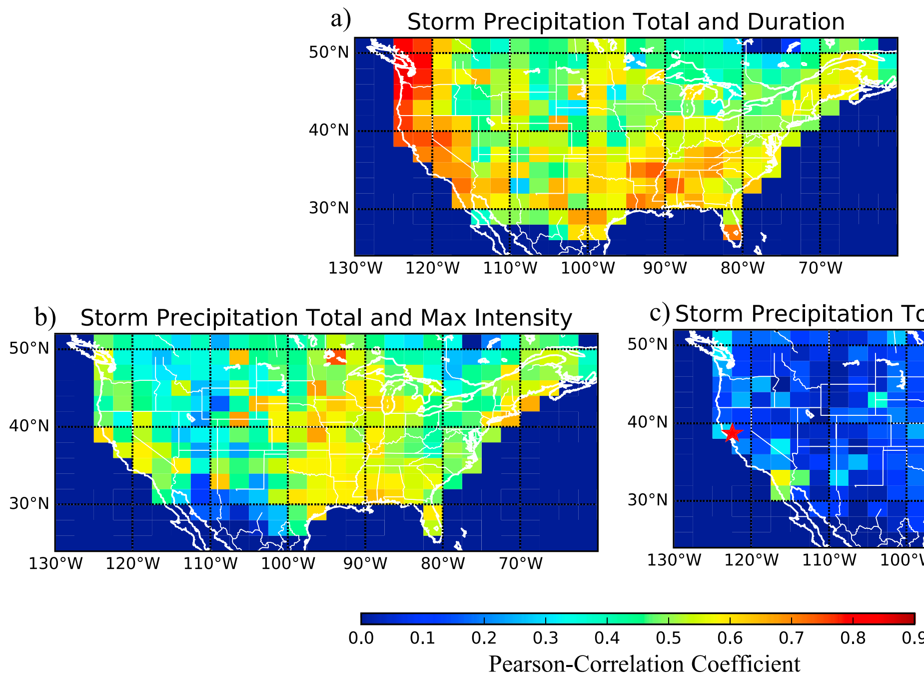

Figure 2. Spatial map of Pearson correlation coefficients of storm precipitation total with (a) storm duration, (b) storm maximum intensity, and (c) storm average intensity for storms observed from 1948 to 2002.

In order to compare the results from coarse spatially gridded CPC precipitation data with point-scale in situ observations, Pearson correlation coefficients were calculated for storm precipitation totals and storm duration, maximum intensity, and average intensity in a 2 min precipitation record from one of the NOAA Hydrometeorology Testbed stations (Cazadero) in the Russian River watershed in northern California (ftp://ftp1.esrl.noaa.gov/psd2/data/realtime/CsiDatalogger/SurfaceMet/czc/) for the period of 2011–2016, following the same methodology described in section 2. The location of this station is shown by the red star in Figure 2c. A range of criteria for minimal zero precipitation hours separating two consecutive storms (0–48 h) and minimal storm precipitation totals (0–15 mm) was used to define storms at this station (Figure 3). Regardless of the criteria used to define storms, precipitation totals have stronger correlations with storm duration (0.7–1) than with storm maximum (0.4–0.7) and average intensities (0.1–0.5), in agreement with the correlations from the gridded CPC precipitation data. Thus, the results here do not appear to be contingent on the gridding applied to the hourly precipitation data by *Higgins et al.* [1996, 2000].

According to these results, storm totals in USWC depend more on storm duration than on maximum or storm-average intensities, and thus, long storms tend to generate the largest amounts of precipitation, potentially contributing more to water resources or leading to extreme floods. In this region, persistent AR conditions have been shown to increase amounts of precipitation remarkably and result in the most streamflow generation [*Ralph et al.,* 2013].

4. Extreme Storms in USWC and Role of ARs

ARs contribute importantly to USWC water resources and are regionally known to be the cause of major floods. Here we explore some characteristics of storms associated with ARs and investigate the role of ARs in USWC extreme storms through the lens of hourly precipitation records. Among all storms that occurred along the USWC from 1948 to 2002, 16–32% were associated with ARs, and on average ARs contributed 31–52% of annual precipitation in this region. The contribution of storms associated with ARs to annual precipitation is largest in northern California (between 36°N and 38°N), in line with the results from previous studies [e.g., *Guan et al.,* 2010; *Dettinger et al.,* 2011; *Kim et al.,* 2013; *Rutz et al.,* 2014].

Using 91 AR events detected based on hourly observations of IWV and terrain-normal component of IWV flux from 2004 to 2010 in California's Russian River, *Ralph et al.* [2013] showed that on average, landfalling ARs

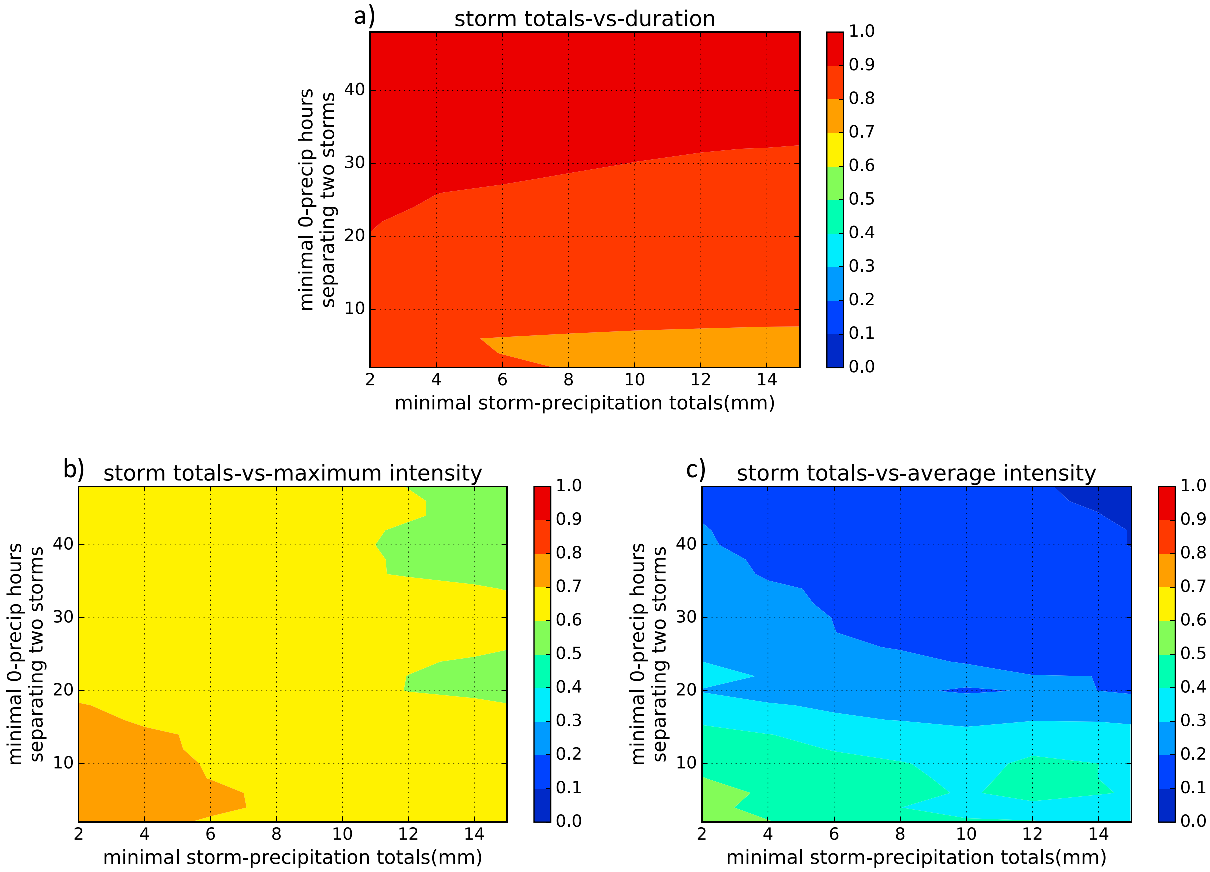

Figure 3. Pearson correlation coefficient of precipitation totals with duration, maximum intensity, and average intensity at Cazadero station (shown by red star in Figure 2c), using 2 min observations from 2011 to 2016.

lasted about 20 h, and that AR events with longer duration yielded larger amounts of precipitation. In the present analysis, this result is extended all along the USWC, using storms defined based on 55 years of hourly precipitation observations. For each coastal grid cell, storms were categorized as either AR or non-AR storms. Frequency distributions of storm total precipitation, duration, average intensity, and maximum intensity of storms in the USWC are presented in Figure 4. Average storm totals, duration, average intensity, and maximum intensity during AR storms are found to be 68%, 48%, 29%, and 33% higher than their mean states, respectively.

Neiman et al. [2008] documented the seasonality of ARs in the Eastern Pacific and showed that warm season (April–September) ARs are generally weaker and result in much less precipitation relative to cool season ARs. Comparing the distribution of warm season AR storms with cool season AR storms in USWC confirms these results and indicates that warm season AR storms are generally shorter and weaker and produce less amounts of precipitation and, therefore, are less probable to cause severe floods. Moreover, the frequency of cool season AR storms along the USWC is notably larger than the frequency of warm season AR storms, thus dominating the overall distribution of AR storms characteristics (Figure 4; black dotted lines, blue solid lines, and red dashed lines represent distribution of all-year, cool season, and warm season AR storms, respectively).

As discussed previously, ARs are known to yield extreme precipitations and major floods along the USWC. Here the role of ARs in USWC extreme storms is explored in more detail by studying the relationships between the fraction of storms associated with ARs in cool and warm seasons and their corresponding storm characteristics. The fraction of storms associated with ARs is larger for storms that yield larger precipitation totals, so that 60–80% of storms with totals larger than about 50 mm are associated with ARs (presented by white triangles and color shadings in Figure 4a). ARs are more prevalent among the

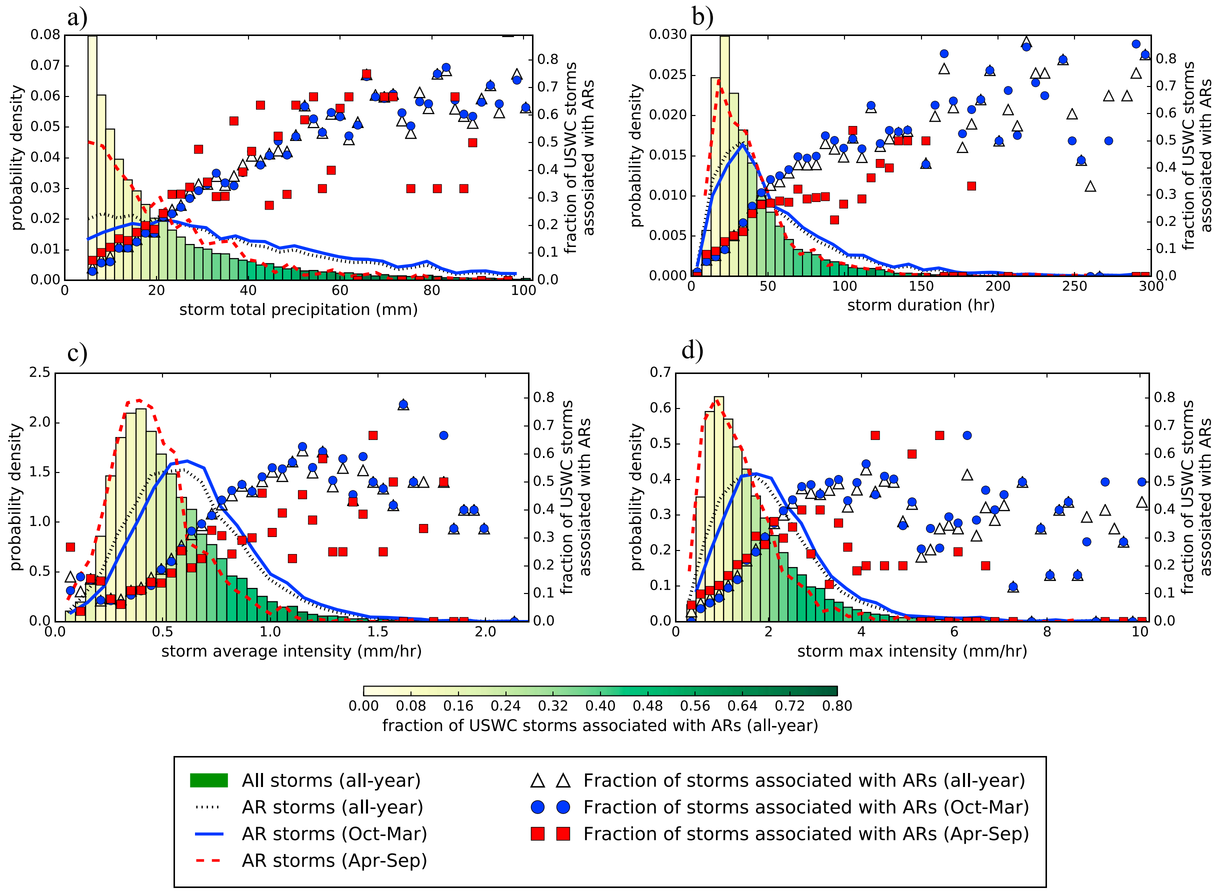

Figure 4. PDF of (a) storm totals, (b) storm duration, (c) average storm intensity, and (d) maximum storm intensity for all storms, all-year AR-associated storms, cool season (October–March) AR-associated storms, and warm season AR-associated storms in USWC coastal grid cells are shown by bars, dotted black lines, solid blue lines, and dashed red lines, respectively. The colors of bars represent the fraction of storms in each bin that are associated with ARs. The fraction of all-year, cool season, and warm season storms that are associated with ARs is shown by white triangles, blue circles, and red squares, respectively.

more persistent storms (Figure 4b), which generally result in heavy precipitation along the USWC, than among short-duration storms.

The fraction of storms associated with ARs also are larger for storms with average and maximum intensity greater than about 1.2 and 4 mm h^{-1}, respectively (Figures 4c and 4b). However, among storms with even greater intensities, the fractions of storms associated with ARs do not increase smoothly and instead are quite variable, spanning a wide range of 0–70%. This variability is partly due to the reduced sample number towards the tail of the intensity distributions. However, extreme storms along the USWC are among longest storms and thus can span a wide range of average and maximum intensities, from weak to strong.

Examining cool season versus warm season AR storms (blue versus red lines and markers in Figure 4) highlights the fact that the prevalence of ARs among extreme storms along the USWC is larger in the cool season. The role of ARs in establishing the relation between longer and larger storms is also clearest in the cool season. These findings are consistent with previous observations that warm season ARs are generally weaker and yield much less precipitation totals than cool season ones [*Neiman et al.*, 2008].

To better understand the role of ARs in the USWC extreme storms and its importance in applications such as water resource management and flood risk mitigation, the contribution of ARs to the storms with storm totals recurrence intervals longer than 2 years are considered next. A 2 year return interval is selected here to identify large storms in USWC, because these storms are large enough to help to replenish water resources after elongated drought episodes, cause major erosion and debris flow, and result in some major floods. Furthermore, since 55 years of precipitation observations are used in this study, choosing a return interval longer than 2 years would reduce the sample size and reduce reliability of the results. Figure 5 presents

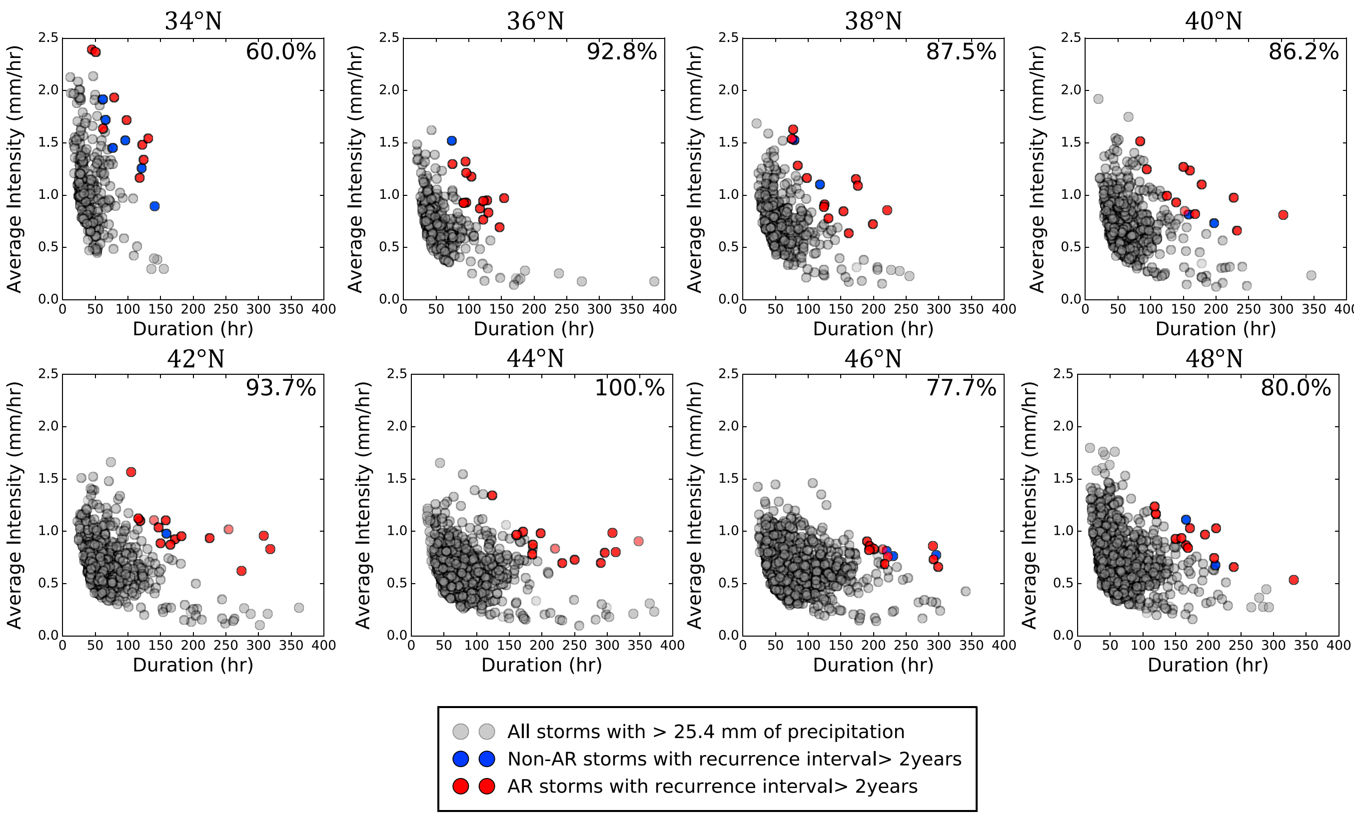

Figure 5. Average intensity-duration plots for storms at coastal grid cells along the USWC from 34°N to 48°N. Only the storms with precipitation accumulations larger than 25.4 mm are shown in these figures (shown by gray circles) to avoid including a large number of relatively small storms, as the focus of this plot is on the most extreme storms along the USWC. Storms with recurrence interval longer than 2 years based on storm totals are colored as red and blue to represent AR storms and non-AR storms, respectively.

average intensity-duration plots for the coastal grid cell storms from 34°N to 48°N along the USWC. Storms with recurrence intervals longer than 2 years are colored as red and blue circles to represent AR and non-AR storms, respectively. Remarkably, 78–100% of the storms with recurrence intervals longer than 2 years in northern California, Oregon, and Washington are associated with ARs in USWC, while in southern California only 60% of these storms are AR related. These results are consistent with previous studies, identifying ARs as the major cause of river floods in USWC [*Ralph et al.,* 2006; *Neiman et al.,* 2011; *Dettinger and Ingram*, 2013; *Ralph et al.,* 2014]. As shown in Figure 5, large storms with recurrence interval longer than 2 years are generally within the top 10% longest storms, while their average intensity has a wide range from weak to strong. These characteristics of large storms are in line with the strong correlation between storm total precipitation and duration observed in USWC and highlight the importance of storm duration for determining storm totals and potential impacts in this region.

AR events used in this study are defined solely based on atmospheric conditions (length, width, and intensity of IVT plumes), without inclusion of precipitation in the definition. Thus, the dominant role that ARs, and especially duration of AR storms, play in the arrival of extreme storms is not a foregone conclusion. This dominance highlights the value of AR awareness in forecasting and analysis of major storms and floods on the USWC [*Lavers et al.,* 2016]; recognizing the arrival of ARs in observations or forecasts clarifies flood risks, and forecasting AR durations is particularly important over the course of many storms.

5. Conclusions

Storms range from weak to extreme, and, depending on where they are along this spectrum, they have the potential to be beneficial, replenishing water resources and ending prolonged drought episodes, or to be hazardous, resulting in socioeconomic losses from floods, debris flows, and landslides. Storms defined as continuous stretches of precipitation in hourly records from 1948 to 2002 are studied here to evaluate their characteristics. In CONUS, USWC and SEUS have the largest average storm-total precipitations. These two regions were shown by *Ralph and Dettinger* [2012] to have the largest 3 day precipitation totals in the U.S. Analyzing storm characteristics in these two regions reveals that, on average, USWC storms have relatively long duration and low intensity compared to the SEUS storms, highlighting differences between storm mechanisms in these areas. Storm-total precipitation is more closely related to storm duration than to storm intensity, especially in USWC where total-versus-duration correlation coefficients are 0.7 to 0.9. This emphasizes the importance of improving the skill of weather forecasts of the duration of storms. This is particularly important in practice because storms with longer duration have higher potential to cause severe floods over large areas.

In terms of extremes storms in the USWC, using the hourly data analyzed here, ARs are found to be larger, longer, and have higher-than-average intensities during the period of record (1948–2002). Cool season AR storms yield significantly more precipitation than warm season AR storms, in line with previous studies. The percentages of ARs among USWC storms increase for storms with larger precipitation totals and for storms with longer durations, until—for the largest storms—60–80% are associated with ARs in the cool season. The fraction of storms associated with ARs also increases as the average and maximum intensity of storms increase up to 1.2 and 4 mm h^{-1}, respectively. The fractions of AR storms with still higher intensities are highly variable and range from 0 to 70%.

Average intensity-duration graphs for USWC storms reveal that storms with greater than 2 year recurrence intervals (based on storm precipitation totals) are dominantly associated with ARs in the USWC coastal grid cells. The duration of large storms with recurrence intervals longer than 2 years are generally within the top 10% longest storms, whereas their average and maximum intensities vary widely, consistent with high correlation observed between storm duration and storm total precipitation in this region.

Thus, storm duration plays an important role modulating the size and impacts of storm totals, especially in the USWC. Improving skill of forecasts of duration of storms in USWC should be a particular priority, as durations provide valuable information that could be used to enhance water reservoir management and flood risk mitigation. ARs are verified as major contributors to the largest storms in this region, and the present study indicates that regionally and over the several decades considered here, ARs play this important role because they tend to be of longer durations with relatively intense precipitation than other storm types. More research is required to disentangle the relationship between storm duration, storm intensity, and the resultant streamflows at these regional and hourly scales. Impacts of AR duration and intensity on resulting storm characteristics such as duration, intensity, and storm total precipitation also need to be explored in more details and can enhance the skill of extreme storm and flood forecasts. Considering the stronger relations between storm durations and storms totals—rather than storm intensities and storm totals—especially along the USWC, more effort should be focused on predicting changes in storm durations, including especially landfalling ARs, in response to climate change with increasing greenhouse gas concentrations in the atmosphere.

Acknowledgments
The gridded hourly precipitation data set used in this study is available from the NOAA/Office of Atmospheric Research/Earth Systems Research Lab Physical Sciences Division, Boulder, Colorado, USA, and was downloaded from http://www.esrl.noaa.gov/psd/ on 5 December 2016. The AR landfall record used is a part of the global AR database available at https://ucla.box.com/ARcatalog produced by the algorithm described in *Guan and Waliser* [2015]. Hourly precipitation observations from NOAA Hydrometeorology Testbed (HMT) at Cazadero were downloaded from ftp://ftp1.esrl.noaa.gov/psd2/data/realtime//CsiDatalogger/SurfaceMet/czc on 1 April 2017. This study is supported by the U.S. Army Corps of Engineers (USACE)-Cooperative Ecosystem Studies Unit (CESU) as part of Forecast Informed Reservoir Operations (FIRO) under grant W912HZ-15-2-0019. Participation of M.D. was supported by the USGS National Research Program with funding from the Sonoma County Water Agency.

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