Title
The Shifting Scales of Western U.S. Landfalling Atmospheric Rivers Under Climate Change

Permalink
https://escholarship.org/uc/item/2140k478

Journal
Geophysical Research Letters, 47(17)

ISSN
0094-8276

Authors
Rhoades, AM
Jones, AD
Srivastava, A
et al.

Publication Date
2020-09-16

DOI
10.1029/2020GL089096

Peer reviewed
The Shifting Scales of Western U.S. Landfalling Atmospheric Rivers Under Climate Change

Alan M. Rhoades¹, Andrew D. Jones¹, Abhishekh Srivastava², Huanping Huang¹, Travis A. O’Brien¹,³, Christina M. Patricola¹,⁴, Paul A. Ullrich¹,², Michael Wehner⁵,⁶, and Yang Zhou¹

¹Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA, ²Department of Land, Air, and Water Resources, University of California, Davis, CA, USA, ³Earth and Atmospheric Sciences Department, Indiana University, Bloomington, Bloomington, IN, USA, ⁴Department of Geological and Atmospheric Sciences, Iowa State University of Science and Technology, Ames, IA, USA, ⁵Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract  Atmospheric rivers (ARs) can be a boon and bane to water resource managers as they have the ability to replenish water reserves, but they can also generate million-to-billion-dollar flood damages. To investigate how anthropogenic climate change may influence AR characteristics in the coastal western United States by end century, we employ a suite of novel tools such as variable resolution in the Community Earth System Model (VR-CESM), the TempestExtremes AR detection algorithm, and the AR category scale. We show that end-century ARs primarily shift from being “mostly or primarily beneficial” to “mostly or primarily hazardous” with a concomitant sharpening and intensification of winter season precipitation totals. Changes in precipitation totals are due to a significant increase in AR (+260%) rather than non-AR (+7%) precipitation, largely through increases in the most intense category of AR events and a decrease in the interval between landfalling ARs.

Plain Language Summary  Atmospheric rivers are central to water resource management in the western United States. Anthropogenic climate change has and continues to alter these storms, which has a cascade of societally relevant impacts. We evaluate how end-century atmospheric river behavior is altered, assuming little-to-no carbon mitigation occurs. To do this, we use a state-of-the-art global climate simulation that allows us to connect global-to-regional scales and, compared with conventional global climate models, better represent the interactions between atmospheric rivers and mountains when they make landfall. To isolate changes in atmospheric river behavior in our simulations, we use a newly developed atmospheric river detection algorithm and category scale devised to communicate risk more clearly. Using these tools, we find that by end-century atmospheric river character shifts from being “mostly or primarily beneficial” to “mostly or primarily hazardous.” This results in increased precipitation totals, primarily from the most hazardous atmospheric rivers, resulting in a sharpening and intensification of the water year. Some end-century atmospheric rivers exceed the highest levels of the category scale; however, we do not find that any single storm produces significantly more precipitation. Therefore, the increased precipitation is due to an increase in the number of hazardous atmospheric rivers that more regularly occur back-to-back.

1. Introduction

The transport of water vapor, or integrated vapor transport (IVT), from the equator to high latitudes is largely driven by filamentary structures known as atmospheric rivers (ARs) (Gimeno et al., 2014; Newell et al., 1992; Payne et al., 2020). These mechanisms of poleward vapor transport are characterized by coherent structures of IVT, on average 3 km deep, 850 km wide, and thousands of kilometers long (Ralph et al., 2018). Mechanistically, ARs can be thought of as the footprints of extratropical cyclone paths where the strength of the entrainment of warmer, moister air near their cold fronts dictate AR intensity (Dacre et al., 2019). Importantly, as ARs are transported across oceanic basins and make landfall, their water vapor potential is realized through cooling mechanisms that result in precipitation (e.g., orographic uplift).
For coastal regions of the western United States, ARs provide a clear water resource boon and are often heralded for their drought busting capabilities (Dettinger, 2013; Wang et al., 2017). For example, in California, AR-induced precipitation accounts for 25–50% of accumulated precipitation totals (Dettinger et al., 2011; Lamjiri et al., 2018) and 22–73% of winter season snowpack (Guan et al., 2010, 2013). This precipitation often occurs in under 120 hr each year (Lamjiri et al., 2018) through a limited number of events (Neiman et al., 2008; Payne & Magnusdottir, 2014; Waliser et al., 2012). However, the strongest ARs, or even a tightly coupled series of ARs, can also be a bane to resource managers through extreme precipitation, high winds, abrupt runoff, avalanches, and destabilization of hillslopes and built infrastructure (Cordeira et al., 2019; Fish et al., 2019; Hatchett et al., 2017; Oakley et al., 2018; Vano et al., 2019; Waliser & Guan, 2017). This was starkly evident during the 2017 water year in California, the most active AR season since, at least, the midtwentieth century (Gershunov et al., 2017), when the state's second-largest manmade reservoir, Lake Oroville, was nearly destabilized by the extreme precipitation from back-to-back ARs that, in combination with a large antecedent snowpack, resulted in abrupt snowmelt (White et al., 2019).

To better quantify the boon or bane aspects of AR events, Ralph, Rutz, et al. (2019) developed an AR category scale akin to those used for other hydrometeorological extremes (e.g., hurricanes). Practically, this scale describes the spectrum of ARs as “primarily beneficial” (Cat 1) to “primarily hazardous” (Cat 5) to water resource management. Cat 1 through 3 AR events were shown to produce comparable 3-day storm total precipitation amounts, whereas Cats 4 and 5 AR events were much warmer, rain inducing (even at higher elevations), and associated with extreme runoff. Fiscally, AR Cats 1 and 2 events often produce flood damages <$1 million, whereas AR Cat 4 to 5 events, in some instances, can inflict damages >$1 billion (Corringham et al., 2019). For example, Ralph, Rutz, et al. (2019) showed that all 11 major floods that occurred in a Northern California watershed (Russian River) were associated with Cat 5 AR events, with some storm totals reaching beyond 500 mm (Ralph & Dettinger, 2012), and Florsheim and Dettinger (2015) indicated that 81% of California Central Valley levee breaks coincided with AR landfalls.

Given the important water resource management and socioeconomic impacts associated with differences in AR categories, a critical question is how landfalling ARs may change in the future under anthropogenic climate change. Global climate models have been useful tools to study how anthropogenic climate change induced dynamical and thermodynamical changes may influence future North Pacific AR characteristics and western U.S. precipitation response (Benedict et al., 2019; Dettinger, 2011; Gershunov et al., 2019; Gao et al., 2015; Hagos et al., 2016; Payne & Magnusdottir, 2015; Payne et al., 2020; Shields & Kiehl, 2016a, 2016b; Swain et al., 2016a; Warner et al., 2015). However, many of these studies have conventionally used 1.00–2.50° grid spacing to evaluate these effects which, as noted by Payne et al. (2020), may underestimate important processes that shape the precipitation efficiency of landfalling ARs due to orographic uplift and microphysical processes. To try and circumvent model resolution constraints, studies like Gershunov et al. (2019) utilize statistical downscaling techniques. These statistical downscaling techniques enhance the spatial heterogeneity of the original climate model outputs and, in some cases, bias correct the historical simulations toward observations (Pierce et al., 2014). However, with a particular focus on extreme precipitation and future AR events, these techniques can also incorporate stationarity by training the statistical relationships over a fixed historical period with the assumption that the spatial relationship between the local and large-scale fields will not change in the future, which may not be the case if changes to landfalling AR character occurs.

Uniform high-resolution (0.25°) global climate model simulations have been conducted, or will be conducted in the High Resolution Model Intercomparison Project (HighResMIP Haarsma et al., 2016), and may help reduce some of the known topographic related biases that influence simulated landfalling ARs. However, due to their large computational, storage, and data transfer demands few simulations have been completed and/or become widely accessible (Bacmeister et al., 2014; Gutjahr et al., 2019; Hagos et al., 2015; Roberts et al., 2019, 2020; Wehner et al., 2014) and most have a select number of simulated years and/or sub-daily output variables. Furthermore, global climate models, even at the resolutions run for HighResMIP, may still under represent coastal topography (e.g., Cascades) and may not ameliorate long-standing biases in precipitation due to drizzle events, fixed resolution assumptions in sub-grid-scale physics schemes, and nonconvergence of extreme precipitation through horizontal resolution refinement alone (Chen & Dai, 2018, 2019; Herrington & Reed, 2020, 2017; Rhoades, Ullrich, et al., 2018; Wehner et al., 2014). Yet, global climate models are one of the only ways in which to assess the nonlinear effects of climate change on AR behavior, particularly the interplay between dynamical and thermodynamical responses to climate
change and their influences on IVT (Payne et al., 2020). Variable-resolution global climate modeling techniques are a means to bridge this global-to-regional scale mismatch and have been used extensively to investigate various aspects of western U.S. hydroclimate (Gettelman et al., 2018; Goldenson et al., 2018; Huang et al., 2016; Rhoades et al., 2016; Rhoades, Ullrich, & Zarzycki, 2018; Rhoades, Ullrich, et al., 2018; Rhoades et al., 2020; Wu et al., 2017; Wang & Ullrich, 2018; Xu et al., 2018).

Therefore, the aim of this study is to leverage the variable-resolution capabilities in the Community Earth System Model (VR-CESM) to assess three main questions regarding historical versus end-century AR related impacts in coastal states of the western United States, including the following:

1. Is VR-CESM a viable modeling option to explore landfalling AR characteristics over a near-term historical period (1985–2015)?
2. How much do landfalling AR characteristics (e.g., Ralph, Rutz, et al., 2019, AR categories) change between the historical period and end-century period (2070–2100)?
3. How do changes in landfalling AR characteristics between these two periods influence the nature of precipitation (e.g., seasonality, intensity, storm totals, and return periods)?

2. Methods

2.1. Simulation of ARs

The 30-year historical (1985–2015) and end-century (2070–2100) simulations of western U.S. landfalling ARs are performed using the CESM Version 2.0 with Atmospheric Model Intercomparison Project (AMIP) protocols (Collins et al., 2006; Danabasoglu et al., 2020; Gent et al., 2011; Hurrell et al., 2013). AMIP simulations dynamically couple the atmospheric model (Community Atmosphere Model Version 5.4, CAM5.4) with the land surface model (Community Land Model Version 5.0, CLM5.0) and constrain the simulation with monthly prescribed ocean conditions (Gates et al., 1999). CAM5.4 with the spectral element dynamical core is employed to enable the utilization of unstructured grids (Guba et al., 2014; Lauritzen et al., 2018; Ullrich, 2014; Zarzycki et al., 2014). Figure S1 in the supporting information shows the variable-resolution 28-km refinement domain and western U.S. topographic representation. Although 28-km refinement is cutting edge from a global climate modeling perspective, we do note that certain features of coastal western U.S. topography are still under resolved (e.g., Cascades). In the end-century simulation, Representative Concentration Pathway (RCP) 8.5, or the high-emissions scenario, is employed and run analogous to Rhoades, Ullrich, and Zarzycki (2018). Details of the model setup and historical validation of the western U.S. hydroclimatology of these simulations is described by Rhoades et al. (2020). We briefly note that daily climate average VR-CESM water year precipitation totals in the mountainous western United States were comparable to two widely used, station-based reanalyses (5% difference). However, snow water equivalent and 2-m surface temperature were significantly low and high biased, respectively, which is why we do not assess AR versus non-AR precipitation phase changes in this study.

2.2. Landfalling AR Detection and Categorization

TempestExtremes (TE) (i.e., the SpineARs and StitchBlobs algorithms) is employed to detect AR events (Ullrich & Zarzycki, 2017; Zarzycki & Ullrich, 2017). When used out-of-the-box TE is close to the median of all 20 Atmospheric River Tracking Method Intercomparison Project (ARTMIP) algorithms in terms of global AR area and poleward moisture flux and storm duration along the western United States (Rutz et al., 2019). TE is considered more of a “relative threshold” based AR detector, meaning that it is minimally sensitive to changes in background IVT, which may have important implications for assessing future ARs. These two points are important as AR count and characteristics at landfall, such as in Bodega Bay of California (Ralph, Wilson, et al., 2019), and AR-associated precipitation, particularly in the California Sierra Nevada (Huning et al., 2017, 2019), has been shown to be influenced by the choice of AR detection algorithm. The landfalling AR characteristics are summarized using a novel extension to TE with more explicitly defined AR detection parameter choices discussed in Rhoades et al. (2020).

The Ralph, Rutz, et al. (2019) AR category scale is informed by years of globally coordinated AR algorithm development, ARTMIP (Rutz et al., 2019; Shields et al., 2018), and a recent assessment of western U.S. historical return periods for different IVT thresholds (Dettinger et al., 2018). Formally, this AR scale relates the maximum IVT reached by a given AR event (i.e., correlates with maximum precipitation rates) with the duration of its landfall (i.e., correlates with storm total precipitation). Importantly, in this study, if ARs
exceed categories in the top row of the Ralph, Rutz, et al. (2019) AR chart (i.e., >1,500 kg/m/s), they are, depending on their AR duration, included in either Category 4 or 5; this occurs particularly frequently at end century and is consistent with findings in Gershunov et al. (2019). Also, if an AR duration or maximum IVT falls on a split between two Ralph, Rutz, et al. (2019) AR categories the AR event is included in the lower of the two AR categories. Henceforth, Ralph, Rutz, et al. (2019) AR categories will simply be called AR categories (or Cat).

Unique to this study, further extensions were made to leverage TE outputs to produce an AR Cat unique for each landfalling AR event at all grid cells over which the AR occurred with maximum IVT and AR duration determined independently at each grid cell. More specifically, TE provides both binary AR masks (i.e., 0 or 1) and spatiotemporally stitched AR masks with unique AR identifiers (i.e., 1, 2, 3, 4, 5, ..., 4,000). To calculate AR landfall duration, we first identify the time at which the unique AR identifier is present in the region of interest (e.g., coastal states of the western United States) and then accumulate all binary AR masks at each grid cell (i.e., number of time slices, in this case 6-hourly) until the time at which the unique AR identifier does not exist over the region of interest. Similarly, using the duration of the unique AR landfall identifiers over a given region, we identify the maximum IVT reached at each grid cell. Independent estimates of both AR landfall duration and maximum IVT reached are then used to compute the AR Cat reached at each grid cell.

AR-associated precipitation is computed by first calculating each individual landfalling AR’s average precipitation rate over its total landfall duration. All precipitation that occurs over the three coastal states is associated with a given AR from the start of landfall through termination and computed as a precipitation total. We then bin the individual AR precipitation totals into the maximum AR category reached at any one grid cell over the lifetime of the AR. Last, we sum the total amount of precipitation across both 30-year historical and end-century periods and distinguish those totals from non-AR-induced precipitation.

Figure S2 shows the AR Cats, the components used to compute each AR Cat (i.e., maximum IVT and landfall duration), and storm total precipitation for three of the most impactful ARs simulated by VR-CESM. One key assumption made in this manuscript is that although we independently assess maximum IVT and landfall duration for each AR over all coastal western U.S. state grid cells, we sometimes distill each AR down to the grid cell of maximum IVT and/or AR Cat reached. Similarly, AR precipitation totals are assigned to the maximum AR Cat reached by the AR over its landfall lifetime, even though a spectrum of AR Cats can be reached in a single AR. We assume this to be a good approximation given that each AR spans a large area, the location of maximum storm total precipitation and AR Cat reached do not always collocate, and, from an impacts perspective, an AR would likely be associated with its maximum AR Cat reached over its entire area that it made landfall. However, this assumption may influence the overall counts of lower category ARs between the historical and end-century periods.

2.3. Extreme Value Analysis of AR and Non-AR Precipitation

Since AR and non-AR precipitation may respond to climate change in different ways (e.g., Gershunov et al., 2019), it is instructive to estimate projected changes in extreme precipitation intensities due to AR and non-AR events. To do this, we perform univariate extreme value analysis (EVA) to estimate changes in return values of AR and non-AR related extreme precipitation for 2-, 5-, 10-, and 25-year return periods. The EVA employs fitting the generalized extreme value (GEV) distribution to data in the form of block maxima (here, 6-hourly annual maximum precipitation (AMP)). We compute AMP from each water year (1 October to 30 September) over the 30-year historical and end-century periods, respectively. We also perform non-parametric Mann-Kendall trend test (Mann, 1945) to detect locations with significant trend in AMP data. Since we found significant trends ($p = 0.05$) in less than 5% of locations, we used the stationary model of the GEV distribution. Further details of the GEV analysis are given in Coles et al. (2001).

3. Results

3.1. Historical Validation of VR-CESM

To evaluate if VR-CESM is a viable modeling option to study western U.S. landfalling ARs, we first evaluate it against a state-of-the-art reanalysis data set over a similar 30-year historical period (1985–2015). The
Due to ERA5 being relatively new, few western U.S. AR studies have utilized it to date. Several of the more prominent AR studies have used NASA's Modern-Era Retrospective Analysis for Research and Applications Version 1 or 2 (MERRA or MERRA-2) and/or the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalyses (Detttinger et al., 2018; Gelaro et al., 2017; Gershunov et al., 2019; Kalnay et al., 1996; Payne & Magnusdottir, 2014; Ralph, Rutz, et al. 2019; Shields et al., 2018). With that said, studies using the ERA5 predecessor, ERA-Interim, have shown that the reanalysis data set underestimates other extreme meteorological phenomena such as tropical cyclones (Hodges et al., 2017; Murakami, 2014) and, more broadly, daily 90th percentile precipitation (Sun et al., 2018). From an AR perspective, precipitation differences across reanalyses are particularly evident over the North Pacific AR track (e.g., Figure 13 in Sun et al., 2018) and have been shown for coastal western U.S. IVT too (e.g., Figure 3 in Detttinger et al., 2018). Notably, Ralph, Wilson, et al. (2019) has also shown that the AR detection method used, rather than reanalysis data set, has a larger influence on AR counts when evaluated at Bodega Bay in California.

Annual AR summary statistics are shown in Table 1 for both ERA5 and VR-CESM. Similar to Rhoades et al. (2020), we find that VR-CESM produces a comparable number of ARs, longitude of origin, and AR lifetime over the Northeast Pacific with ERA5. However, the number of ARs that make landfall over the coastal western United States is larger by 11 per year. This is further impacted by the fact that the maximum IVT reached and duration for landfalling ARs are also larger. After converting to the AR category scale, an average AR category of 2.45 is found for VR-CESM compared with 2.04 in ERA5 (Figure S3). Temporally, an increased number of AR events are seen across most winter months in VR-CESM; however, a much larger number of AR events occur in late winter to early spring compared with ERA5 (Figure S4) and is consistent across subregions (Figure S5). Spatially, ERA5 and VR-CESM are largely in agreement on the number of grid cells over which Cats 2 and 3 AR events occur (Figure S6). However, ERA5 shows a much more constrained estimate of the highest AR category occurrences across the coastal western U.S. states compared with VR-CESM, particularly Cat 5 events. More specifically, ERA5 suggests that AR Cat 5 events predominantly occur in the Oregon and Washington coasts. While the spatial extents of Cat 5 AR events are similar in VR-CESM in Oregon and Washington, more events occurred further south in coastal California too (e.g., San Francisco Bay Area).

The increased number of ARs, particularly Cats 4–5, largely drive the mismatch in AR versus non-AR precipitation during winter between ERA5 and VR-CESM (Figure S6). Mismatch in total precipitation is highest during midwinter and fairly consistent across subregions, although with the largest difference shown in January in Northern California (Figure S7). ERA5 suggests that ARs account for 17% of the 30-year precipitation totals, whereas VR-CESM suggests 28%. Differences are smallest for non-AR precipitation totals (17% difference, ∼3,200 mm) and highest for AR precipitation totals (57% difference, ∼1,700 mm). More specifically, VR-CESM differences with ERA5 in total precipitation contributed by Cats 1–2 ARs are in most agreement (∼2%, ∼40 mm) while Cats 3 (∼73%, ∼670 mm) and 4–5 ARs (∼260%, ∼1,700 mm) differ considerably. Further, although the 75th percentile AR events produce comparable average storm total precipitation in ERA5 and VR-CESM (∼10 mm), the largest AR in ERA5 (∼60 mm) produces less than half the average storm total precipitation simulated in VR-CESM (∼140 mm).

In summary, VR-CESM simulates nearly five-times the number of ARs that meet the AR Cat 5 criteria than ERA5 and nearly 2 times the number of AR Cat 4 (Table S1). This leads to a mismatch in AR-contributed total precipitation (∼57%), particularly from Cats 4–5 ARs. However, we caveat these findings by comparing with the MERRA-2-based results in Ralph, Rutz, et al. (2019). Although not directly comparable to this study, due to evaluation at a single-point location in Northern California (Bodega Bay) and slightly different
Figure 1. Historical (left) and end-century (right) simulated AR events (black dots) that made landfall in the coastal states of the western United States (gray mask region) overlain on the Ralph, Rutz, et al. (2019) AR category scale. Each point is representative of the AR duration at the geographic location where the maximum IVT occurs for each landfalling AR. A linear equation (bottom left), regression fit (black line), and AR count totals within each AR subcategory (upper left corner of each box) are shown.

AR metrics, ERA5 has a larger number of Cat 4 ARs compared to MERRA-2 (22 events in MERRA-2, or 2.4% of events) and less Cat 5 ARs (10 events in MERRA-2, or 1.1% of events) potentially indicating an under representation of Cat 5 ARs in ERA5. We also note that in Rhoades et al. (2020) the same historical VR-CESM simulation used in this study was within 5% of the daily climate average accumulated precipitation estimated by two widely used, station-based reanalyses (although evaluated within the mountainous western United States).

3.2. Shifts in End-Century AR Characteristics

At end century the total number of ARs over the North Pacific per year decreases by 23; however, the number of western U.S. landfalling ARs increases by 11 (Table 1). Using the Kolmogorov-Smirnov two-sample statistical significance test, we find that the increase in landfalling ARs at end century is statistically significant ($p = 0.047$), assuming a significance level of $p = 0.05$. This is irrespective of the westward longitudinal shift ($\sim 1.7^\circ$) in average AR origin by end century over the North Pacific (Table 1). A southward shift in landfall location of ARs along the west coast ($\sim 0.85^\circ$) is also found, although notably the 95% confidence intervals overlap for historical and end-century simulations and this result could be model dependent. Further, end-century ARs that travel through the North Pacific and eventually make landfall are larger, occupying more than double the number of grid cells over their entire lifetime, having more than a half-day longer duration after landfall, and with landfall maximum IVT values that regularly exceed 1,000 kg/m/s, or $\sim 190$ kg/m/s higher average than historical. These findings, particularly a decrease in the number of ARs but increase in AR width and length, are consistent with a global assessment of changes in AR character under a high-emissions scenario across 21 global climate models (Espinoza et al., 2018).

As shown in Figure 1, the combination of the aforementioned factors leads to both an increase in the number of AR events that make landfall in the coastal western U.S. states by end century, as well as a large relative shift in the number of AR events that are “mostly or primarily beneficial” to “mostly or primarily hazardous” to water resources. More specifically, the total number of AR Cats 1 and 2 events historically (550 AR events) occupy the majority of all AR events that make landfall (73%). However, by end century there are relatively fewer Cats 1 and 2 ARs (506 AR events, or 53% of the total), and the distribution of AR events is shifted toward Cat 3 (196 AR events, or 20%) and, importantly, Cat 4 or 5 ARs that are “mostly or primarily hazardous” to water management (260 AR events, or 27%). In particular, the number of Cats 4
Figure 2. Historical (left), end century (center), and difference in (right) AR- versus non-AR-induced monthly precipitation totals, across the respective 30-year periods, for the coastal states of the western United States (gray mask region) binned by the maximum Ralph, Rutz, et al. (2019) AR category reached over the AR landfall lifetime. The percentage of total 30-year precipitation contributed by ARs are shown above each bar.

and 5 ARs increase by more than 2 times and 3.5 times, respectively, compared with the historical simulations (Table S1). The increases in the number of Cats 4 and 5 ARs is consistent with the multimodel results of Gershunov et al. (2019) who also indicate stronger and more longer-lasting ARs with warming. Also, a significant number of AR events exceeded the AR category scale: 73 events had a max IVT >1,500 kg/m/s and duration >6 hr, with 2 AR events exceeding 2,000 kg/m/s and 11 AR events exceeding 72 hr in duration. Recall that in Corringham et al. (2019), Cats 4 and 5 ARs that make landfall in the western United States were associated with median flood damages that were $20 and $260 million, respectively, and in some instances exceeded $1 billion, implying that end-century ARs could become routinely destructive.

The total number of AR landfalls between the 30-year periods increases across all months in the coastal states of the western United States (Figure S9). In winter months (December through March), a consistent increase in the total number of AR events occurred (26–29 AR events, or 25–36%). An asymmetric response is seen in the shoulder months of the water year with April (+29 events) showing the largest increase in AR landfall events (+94%) and November showing one of the smallest increases (15 events, or a 12% increase). Similarly, a greater increase in AR counts is shown in the southernmost portions of the western United States, Northern [NorCal] and Southern [SoCal] California, than the northernmost regions, Oregon and Washington (Figure S10). For example, a marked percent increase of 110% and 66% (+163 and +257 AR events) is projected for SoCal and NorCal over the future 30-year period, although AR activity was historically less active, whereas a more modest percent increase of 35% and 29% (+201 and +167 AR events) is projected for Oregon and Washington, although AR activity was historically more active.

In addition to the increased number of AR events that occupy higher AR categories by end century, ARs make landfall every 13 days on average rather than every 18 days historically, and a larger number of ARs make landfall within a week of one another with 14 of these back-to-back occurrences versus 9 historically (Table 1). This is notable as the frequency and interval between landfalling ARs is particularly impactful to water resource management, especially if a large antecedent snowpack and/or saturated soil moisture conditions exist (e.g., February 2017 California Oroville Dam event discussed in White et al., 2019).

3.3. End-Century Changes in the Nature of Non-AR and AR Precipitation

Thus far, we have primarily discussed the intensity, location, and timing of landfalling ARs; here we focus on their precipitation characteristic. Figure 2 shows the contribution of AR and non-AR precipitation to the monthly 30-year totals for all coastal states of the western United States. Historically, ARs contribute 28–46% of the precipitation totals in winter months (December–February), have a maximum in January, and account for 28% of the annual precipitation totals; this is comparable to Dettinger et al. (2011) and Lamjiri et al. (2018). By end century, AR contributions to total precipitation are more uniform across winter months (41–49%) and make up a much larger portion of the entire precipitation total (41%). Importantly, end-century AR 30-year precipitation totals increase (+5,320 mm, +260%) significantly more than non-AR (+1,120 mm, +7%). As shown in Figure S11, this finding is consistent even if assessed by individual
Figure 3. Historical estimates and their projected changes (end century minus historical) in 6-hr precipitation for 10- and 25-year return periods. Historical estimates (top row) use the color scale along the right edge of the figure, and projected changes use the color scale along the bottom edge. Stippling shows locations where changes are not significant at the 90% significance level computed from a $z$ statistic as defined in Srivastava et al. (2019). Left panels: Non-AR precipitation. Right panels: AR precipitation. Units are in millimeters per 6-hr.

subregions that emphasize distinct latitude bands. SoCal shows the largest percent increase in AR precipitation totals (+1,543 mm, +270%) and Washington shows the largest absolute increase in precipitation totals (+4,949 mm, +160%). NorCal and SoCal also indicate more of a sharpening in seasonality of 30-year precipitation totals than is found in Oregon and Washington, largely due to increases in AR-contributed precipitation in November–March.

Although AR contributions to the 30-year precipitation totals increase from 28% to 41% by end century across the coastal western U.S. states, the increases are not evenly distributed across AR categories. Historical AR category contributions to AR precipitation totals are somewhat evenly distributed across Cats 1–2 (32%), 3 (25%), and 4–5 (43%). In contrast, end-century contributions across AR category shift toward more Cats 4–5 (67%) than Cats 1–3 (33%), which results in more of the coastal states of the western United States being exposed to “mostly or primarily hazardous” AR events (Figure S8).

Interestingly, even though there are several unprecedented AR events (i.e., exceeding the AR category scale) by end century the nature of precipitation produced by these events does not change substantially. Specifically, historical Cat 5 events produce an average precipitation total of 43 mm, which is comparable to end-century events (40 mm). Even the most extreme of the AR Cat 5 (or unprecedented) events in the 30-year historical and end-century period are comparable. For example, maximum average precipitation intensity and largest total precipitation for any historical AR Cat 5 event (32 AR events) is 25 mm/day and 140 mm, respectively, whereas at end-century AR Cat 5 events (137 AR events) are 27 mm/day and 140 mm. This was noted by Dettinger (2011) and may be related to a weakening of the global north-south temperature gradient by end century, which in turn weakens surface winds and reduces the precipitation efficiency of landfalling
ARs as they interact with coastal mountains. Alternatively, this result could be model dependent, with earlier comparisons with ERA5 showing that VR-CESM historical simulations overproduce the number of and total precipitation contributed by Cat 5 AR events.

With that said, the number of AR Cat 5 events in close temporal proximity to one another increases by end century (successive ARs are sometimes referred to as “AR families”; Fish et al., 2019). This is more readily apparent when assessing the largest 1 month, rather than single event, precipitation total across AR Cat 5 events. Historically, the largest 1-month precipitation total (140 mm) coincides with the largest AR Cat 5 event (January 2000), yet at end century the largest 1-month precipitation total does not coincide with the largest AR event (140 mm), but rather with the number of closely coupled AR Cat 5 events. For example, in January 2078 four AR Cat 5 events produce a precipitation total of 270 mm, nearly double the maximum historical monthly precipitation total derived from Cat 5 AR events. Therefore, although no single AR Cat 5 event at end century generates historically unprecedented precipitation totals, the monthly precipitation total from back-to-back events is unprecedented.

Finally, analyses of projected changes in the mean annual maximum (MAM) precipitation (Figure S12) suggest that both AR and non-AR related MAM precipitation significantly increases over most parts of Washington, Oregon, and California. The largest increases are seen in AR precipitation (10–20 mm), particularly over NorCal. Although we did not perform a targeted analysis of seasonal maximum precipitation, our findings may be model dependent and differ from Pierce et al. (2013) who show a general drying of mid-century spring and autumn precipitation in California across an ensemble of dynamically and statistically downscaled global climate model simulations, particularly in NorCal. Figures 3 and S13 show projected changes in 6-hr, 2- to 25-year precipitation due to AR and non-AR events. The figures show that non-AR precipitation for 2- to 10-year return periods is expected to significantly increase (at least 20%) over most of California, except Los Angeles and San Diego regions, and Washington and Oregon for 2- to 5-year return periods. Interestingly, projected changes in non-AR precipitation are smaller (and even negative) for higher return periods (≥10 year) over most parts of Washington, Oregon, and SoCal. In contrast, particularly over NorCal, increases in non-AR precipitation occur with increasing return periods. AR precipitation for all return periods examined is expected to significantly increase (20–300%) over most of Washington, Oregon and California, save for northern Oregon and SoCal.

The increase in AR precipitation estimates is greater than non-AR precipitation estimates for all return periods, consistent with the multimodel analysis of Gershunov et al. (2019). However, we find that non-AR precipitation estimates also increase in the future, which is inconsistent with Gershunov et al. (2019) who found a decline in non-AR precipitation and thus may be model dependent. We note that AR and non-AR 2- to 25-year precipitation estimates in VR-CESM were compared with ERA5 and, in general, AR precipitation is overestimated (Figure S14). This overestimation is clearly seen when comparing the MAM from VR-CESM with ERA5 (Figure S15) but is consistent with earlier findings (e.g., Cats 4–5 AR-contributed precipitation is much higher in VR-CESM; Figure S6).

4. Discussion and Conclusions

ARs are both a boon and bane to water resource managers through their roles as both drought busters and extreme runoff generators. Over the coming century, climate change is expected to augment the role ARs play in the water year, particularly in the coastal states of the western United States. To better characterize and quantify how the nature and character of ARs may change in this region, we ran the VR-CESM focused over the North Pacific through the western United States at 0.25° resolution for a 30-year historical (1985–2015) and end-century (2070–2100) period. The following conclusions were found:

(1) We show that our 30-year historical VR-CESM simulation agrees with the ERA5 reanalysis on the total number of ARs, longitude of origin, and lifetime over the northeast Pacific yet differ across several landfalling AR characteristics (e.g., +11 landfalling ARs per year and +0.5 average Ralph, Rutz, et al., 2019, AR category). Further, extreme precipitation is higher in VR-CESM than ERA5, specifically Cats 4–5 AR average storm total precipitation and AR-contributed precipitation across the water year.

(2) By end century, under a high-emissions scenario (RCP8.5), the coastal states of the western United States experience an increased number of landfalling ARs across all months, although with notable asymmetric shifts in shoulder months (i.e., larger increases in April than October), which may be model specific (Pierce et al., 2013). In addition, a significant shift in AR categories from “mostly or primarily beneficial”
to “mostly or primarily hazardous” occurs with a number of unprecedented ARs. Notably, unlike the historical period, every month of the water year experiences a Cat 5 AR event.

(3) A net increase of +22% (+6,440 mm) in the 30-year precipitation totals across the coastal western U.S. states is projected by end century. Non-AR precipitation totals are slightly, yet significantly, increased (+7%, +1,120 mm, or +37 mm/year) and AR precipitation totals are markedly and significantly increased (+260%, +5320 mm, or +180 mm/year). This is corroborated through a return period analysis of annual maximum precipitation whereby AR precipitation estimates for 2 to 25 years and non-AR precipitation estimates for ≤10 years are expected to significantly increase over most coastal states of the western United States. Although we did not find any single end-century Cat 5 AR event precipitation total to be historically unprecedented, the increased number of Cats 4 and 5 landfalling ARs and, in particular, back-to-back Cat 5 AR events is and results in a maximum monthly precipitation total nearly double that found in the historical period.

If we normalize the changes in precipitation totals by the coastal western U.S. mean surface temperature change in the simulations, our VR-CESM simulations project a precipitation total increase of 4.6%/K. This is physically consistent with the Clausius-Clapeyron (CC) relationship, which relates the saturation vapor pressure of the atmosphere with temperature (Trenberth et al., 2003) and sets a physical limit of ~7.5%/K on precipitation changes, unless updrafts strengthen (O’Gorman & Schneider, 2009; Pendergrass & Gerber, 2016). We also show that AR precipitation totals increase at a much larger rate (+53%/K) than non-AR precipitation totals (+1.4%/K), which agrees with findings made in Gershunov et al. (2019). A notable caveat is that ERA5 indicated much lower storm total precipitation in Cats 4 and 5 AR events and, more generally, less AR-contributed precipitation across the water year than VR-CESM. The relatively constrained non-AR precipitation changes with warming is a more conservative estimate than has been shown in studies like Allen and Ingram (2002) and Allan et al. (2020) (i.e., ~2–3%/K) but is consistent with energy-budget-related constraints on the hydrological cycle and differences could simply be due to regionality (i.e., western United States vs. global response) and/or specific CESM related sensitivities (e.g., cloud feedbacks). The larger degree of AR precipitation change occurs despite decreases in the total number of ARs and in their precipitation efficiency. Rather, the shift toward more Cat 3+ storms overwhelms these decreases; a higher number of strong ARs results in more AR precipitation. This increase in strong ARs could be a result of tropical widening (Staton et al., 2018), making it easier for midlatitude cyclones to entrain tropical moisture.

The uneven increases in mean versus extreme precipitation found in this study, particularly due to differences in how AR and non-AR events change under climate change, agree with the broader literature (Gershunov et al., 2019; Payne & Magnusdottir, 2015; Pendergrass et al., 2017, 2019; Shields & Kiehl, 2016b, 2016a; Swain et al., 2016a). Comparable to Swain et al. (2018), we find a sharpening in end-century precipitation totals, particularly in Northern California, which has been shown to be related to a more accentuated shift in the North American dipole (Wang et al., 2015, 2017). We show, with more granularity, that this increase is largely due to an increase in the number of Ralph, Rutz, et al. (2019) AR Cat 5 events combined with a decrease in the interval between landfalling AR events. The end-century sharpening and intensification of precipitation totals, combined with substantial reductions in mountain snowpack and more depleted groundwater reserves, will place added pressure on water managers to augment assumptions of stationarity (Allan et al., 2020; Milly et al., 2008; Rhoades, Jones, & Ullrich, 2018; Rhoades, Ullrich, & Zarzycki, 2018).

The ramifications of our findings should come with the caveat that we use a single global climate model run for a 30-year period under a single emissions scenario. Further, there is a notable difference in IVT compared with ERA5, which, in turn, influenced landfalling AR counts, characteristics, and associated precipitation (although we note ERA5 may under represent extremes compared with other reanalysis data sets). Additionally, although the resolution of our VR-CESM simulations is representative of the forefront of global climate model simulations (Haarsma et al., 2016), the topographic resolution still may not be sufficient to completely resolve orographic forcing on and/or precipitation phase partitioning of ARs for certain mountains of the coastal western United States (e.g., Cascades). Further, as mentioned in the introduction, global climate models have had long-standing precipitation biases, particularly nonconvergence of extreme precipitation at more refined horizontal resolutions, which may account for some of the precipitation mismatch between VR-CESM and ERA5. Last, as shown by recent studies by Rutz et al. (2019) and O’Brien et al. (2020), AR algorithm parametric and structural uncertainty is important, particularly in the context of climate change. Future work will aim to address some of these limitations and isolate other impacts associated with changes in landfalling ARs.
Acknowledgments

We would like to acknowledge Sasha Gershunov and another anonymous reviewer for their constructive and thoughtful comments about our manuscript during peer review. This study was funded by the Director, Office of Science, Office of Biological and Environmental Research of the U.S. Department of Energy Regional and Global Climate System (RGCM) "the Calibrated and Systematic Characterization, Attribution and Detection of Extremes (CASCADE)" Science Focus Area (Award DE-AC02-05CH11231) and the "An Integrated Evaluation of the Simulated Hydroclimate System of the Continental US" project (Award DE-SC0016605). Analysis and model simulations were performed by the National Energy Research Scientific Computing Center (NERSC), specifically Cori-Haswell and Cori-KNL supercomputing facilities.

Data Availability Statement

ERA5 is publicly available at the Copernicus Climate Change Service (C3S) Climate Data Store (CDS; https://cds.climate.copernicus.eu/#!/search?text=ERA5). The VR-CESM simulations generated for this study are accessible via a NERSC Science Gateway (https://portal.nersc.gov/archive/home/a/arhoades/Shared/www/Hyperion/).

References

Allan, R. P., Barlow, M., Byrne, M. P., Cherchi, A., Douville, H., Fowler, H. I., et al. (2020). Advances in understanding large-scale responses of the water cycle to climate change. Annals of the New York Academy of Sciences, 1472, 49–75. https://doi.org/10.1111/nyas.14337

Allen, M. R., & Ingram, W. J. (2002). Constraints on future changes in climate and the hydrologic cycle. Nature, 419(6903), 228–232. https://doi.org/10.1038/nature01092

Bacmeister, J. T., Wehner, M. F., Neale, R. B., Gettelman, A., Hannay, C., Lauritzen, P. H., et al. (2014). Exploratory high-resolution climate simulations using the Community Atmosphere Model (CAM). Journal of Climate, 27(9), 3073–3099. https://doi.org/10.1175/JCLI-D-13-00871

Benedict, J. J., Clement, A. C., & Medeiros, B. (2019). Atmospheric blocking and other large-scale precursor patterns of Landfalling Atmospheric Rivers in the North Pacific: A CESM2 study. Journal of Geophysical Research: Atmospheres, 124, 11,330–11,355. https://doi.org/10.1029/2019JD030790

Chen, D., & Dai, A. (2018). Dependence of estimated precipitation frequency and intensity on data resolution. Climate Dynamics, 50(9-10), 3625–3647. https://doi.org/10.1007/s00382-017-3830-7

Chen, D., & Dai, A. (2019). Precipitation characteristics in the community atmosphere model and their dependence on model physics and resolution. Journal of Advances in Modeling Earth Systems, 11, 2352–2374. https://doi.org/10.1029/2019MS001536

Coles, S., Bawa, J., Trenner, L., & Dorazio, P. (2001). An introduction to statistical modeling of extreme values, vol. 208. London: Springer.

Collins, W. D., Bitz, C. M., Blackmon, M. L., Bonan, G. B., Bretherton, C. S., Carton, J. A., et al. (2006). The Community Climate System Model version 3 (CCSM3). Journal of Climate, 19(11), 2122–2143. https://doi.org/10.1175/JCLI3761.1

Copernicus Climate Change Service Climate Data Store (CDS) (2017). Copernicus Climate Change Service (C3S): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview

Corine, J. M., Stock, J., Dettlinger, M. D., Young, A. M., Kalansky, J. F., & Ralph, F. M. (2019). A 142-year climatology of Northern California landslides and atmospheric rivers. Bulletin of the American Meteorological Society, 100(8), 1499–1509. https://doi.org/10.1175/BAMS-D-18-0158.1

Corringham, T. W., Ralph, F. M., Gershunov, A., Cayan, D. R., & Talbot, C. A. (2019). Atmospheric rivers drive flood damages in the western United States. Science Advances, 5(12), eaax4631. https://doi.org/10.1126/sciadv.aax4631

Dacre, H. F., Martinez-Alvarado, O., & Mbengue, C. O. (2019). Linking atmospheric rivers and warm conveyor belt airflows. Journal of Hydrometeorology, 20(6), 1183–1196. https://doi.org/10.1175/JHM-D-18-0175.1

Danabasoglu, G., Lamarque, J.-F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., et al. (2020). The Community Earth System Model version 2 (CESM2). Journal of Advances in Modeling Earth Systems, 12, e2019MS001916. https://doi.org/10.1029/2019MS001916

Dettlinger, M. (2011). Climate change, atmospheric rivers, and floods in California a multimodel analysis of storm frequency and magnitude changes. JAWRA Journal of the American Water Resources Association, 47(3), 514–523. https://doi.org/10.1111/j.1752-1688.2011.00546.x

Dettlinger, M. D. (2013). Atmospheric rivers as drought busters on the U.S. West Coast. Journal of Hydrometeorology, 14(6), 1721–1732. https://doi.org/10.1175/JHM-D-13-0321

Dettlinger, M. D., Ralph, F. M., Das, T., Neiman, P. J., & Cayan, D. R. (2011). Atmospheric rivers, floods and the water resources of California. Water, 3(2), 445–478. https://doi.org/10.3390/w30200445

Dettlinger, M. D., Ralph, F. M., & Rutz, J. J. (2018). Empirical return periods of the most intense vapor transports during historical atmospheric river landfalls on the U.S. West Coast. Journal of Hydrometeorology, 19(8), 1363–1377. https://doi.org/10.1175/JHM-D-17-0247.1

Espinoza, V., Waliser, D. E., Guan, B., Lavers, D. A., & Ralph, F. M. (2018). Global analysis of climate change projection effects on atmospheric rivers. Geophysical Research Letters, 45, 4299–4308. https://doi.org/10.1029/2017GL076968

Fish, M. A., Wilson, A. M., & Ralph, F. M. (2019). Atmospheric river families: Definition and associated synoptic conditions. Journal of Hydrometeorology, 20(10), 2091–2108. https://doi.org/10.1175/JHM-D-18-0217.1

Florsheim, J. L., & Dettlinger, M. D. (2015). Promoting atmospheric-river and snowmelt-fueled biogeomorphic processes by restoring river-floodplain connectivity in California’s Central Valley. In P. F. Hudson, & H. Middelkoop (Eds.), Geomorphic approaches to integrated floodplain management of lowland fluvial systems in North America and Europe pp. 119–141. New York: Springer. https://doi.org/10.1007/978-1-4939-2380-9_6

Gao, Y., Lu, J., Leung, L. R., Yang, Q., Hagos, S., & Qian, Y. (2015). Dynamical and thermodynamical modulations on future changes of landfalling atmospheric rivers over western North America. Geophysical Research Letters, 42, 7179–7186. https://doi.org/10.1002/2015GL065435

Gates, W. L., Boyle, J. S., Covey, C., Dease, C. G., Doutriaux, C. M., Drach, R. S., et al. (1999). An overview of the results of the Atmospheric Model Intercomparison Project (AMIP I). Bulletin of the American Meteorological Society, 80, 29–56. https://doi.org/10.1175/1520-0477(1999)080<0029:AOTRO>2.0.CO;2

Gelaro, R., McCarty, W., Sorensen, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). Journal of Climate, 30(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-05758.1

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Huynke, E. C., Jayne, S. R., et al. (2011). The community climate system model version 4. Journal of Climate, 24(19), 4973–4991. https://doi.org/10.1175/2010JCLI3821.1

Gershunov, A., Shulgina, T., Clemens, R. E. S., Guirguis, K., Pierce, D. W., Dettlinger, M. D., et al. (2019). Precipitation regime change in Western North America: The role of Atmospheric Rivers. Scientific Reports, 9(1), 1–11. https://doi.org/10.1038/s41598-019-46169-w

Gershunov, A., Shulgina, T., Ralph, F. M., Lavers, D. A., & Rutz, J. J. (2017). Assessing the climate-scale variability of atmospheric rivers affecting western North America. Geophysical Research Letters, 44, 7900–7908. https://doi.org/10.1002/2017GL074173
Geophysical Research Letters

10.1029/2020GL089096

Gettelman, A., Callaghan, P., Larson, V. E., Zarrarzycki, C. M., Bacmeister, J. T., Lauritzen, P. H., et al. (2018). Regional climate simulations with the Community Earth System Model. *Journal of Advances in Modeling Earth Systems*, 10, 1245–1265. https://doi.org/10.1002/2017MS001227

Gimeno, L., Nieto, R., Vázquez, M., & Lavers, D. (2014). Atmospheric rivers: A mini-review. *Frontiers in Earth Science*, 2, 2. https://doi.org/10.3389/feart.2014.00002

Goldenson, N., Leung, L. R., Bitz, C. M., & Blanchard-Wrigglesworth, E. (2018). Influence of atmospheric rivers on Mountain Snowpack in the Western United States. *Journal of Climate*, 31(4), 9921–9940. https://doi.org/10.1175/JCLI-D-18-0268.1

Guo, B., Rienecker, M. M., & Zhang, K. (2014). Extreme snowfall episodes linked to atmospheric rivers and surface air temperature via satellite measurements. *Geophysical Research Letters*, 41, L20401. https://doi.org/10.1002/2014GL064969

Hagos, S. M., Leung, L. R., Yoon, J.-H., Lu, J., & Gao, Y. (2016). A projection of changes in landfalling atmospheric river frequency and extreme precipitation over western North America from the Large Ensemble CESM simulations. *Geophysical Research Letters*, 43, 1537–1563. https://doi.org/10.1002/2015GL067392

Hatchett, B. J., Burak, S., Rutz, J. J., Oakley, N. S., Bair, E. H., & Kaplan, M. L. (2017). Avalanche fatalities during atmospheric river events in the Western United States. *Journal of Hydrometeorology*, 18(5), 1359–1374. https://doi.org/10.1175/JHM-D-16-0219.1

Herrington, A. R., & Reed, K. A. (2017). An explanation for the sensitivity of the mean state of the community atmosphere model to horizontal resolution on aquaplanets. *Journal of Climate*, 30(13), 4781–4797. https://doi.org/10.1175/JCLI-D-16-06096.1

Herrington, A. R., & Reed, K. A. (2020). On resolution sensitivity in the Community Atmosphere Model. *Quarterly Journal of the Royal Meteorological Society*. https://doi.org/10.1002/qj.3873

Hodges, K., Gage, D., & Naylor, D. (2017). How well are tropical cyclones represented in reanalysis datasets? *Journal of Climate*, 30(14), 5243–5254. https://doi.org/10.1175/JCLI-D-16-0517.1

Huang, X., Rhoades, A. M., Ulrich, P. A., & Zarzycki, C. M. (2016). An evaluation of the variable-resolution CESM for modeling extreme snowfall events linked to atmospheric rivers and surface air temperature via satellite measurements. *Geophysical Research Letters*, 43, L20401. https://doi.org/10.1002/2014GL064969

Huang, B., Rienecker, M. M., & Zhang, K. (2014). Extreme snowfall episodes linked to atmospheric rivers and surface air temperature via satellite measurements. *Geophysical Research Letters*, 41, L20401. https://doi.org/10.1002/2014GL067392

Huntington, L. S., Guan, B., Waliser, D. E., & Lettenmaier, D. P. (2019). Sensitivity of seasonal snowfall attribute to atmospheric rivers and their reanalysis-based detection. *Geophysical Research Letters*, 46, 794–803. https://doi.org/10.1029/2018GL080783

Huntington, L. S., Margulis, S. A., Guan, B., Waliser, D. E., & Lettenmaier, D. P. (2017). Implications of detection methods on characterizing atmospheric river contribution to Seasonal Snowfall Across Sierra Nevada, USA. *Geophysical Research Letters*, 44, 10,445–10,453. https://doi.org/10.1002/2017GL075201

Hurrell, J. W., Holland, M. M., Geist, P. R., Ghan, S., Kay, J. E., Kushner, P. J., et al. (2013). The community earth system model: A framework for collaborative research. *Bulletin of the American Meteorological Society*, 94(9), 1339–1360. https://doi.org/10.1175/BAMS-D-12-00112.1

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, 77(3), 3–437. https://doi.org/10.1175/1520-0477(1996)077<003:TBANMR>2.0.CO;2

Lamjiri, M. A., Dettlinger, D. M., Walsh, J. F., Oakley, N. S., & Rutja, J. J. (2018). Hourly analyses of the large storms and atmospheric rivers that provide most of California’s precipitation in only 10 to 100 hours per year. *San Francisco Estuary and Watershed Science*, 16(4), 1. https://doi.org/10.15444/sfews.2018.16iss4art1

Lauritzen, P. H., Nair, R. D., Herrington, A. R., Callaghan, P., Goldhaber, S., Dennis, J. M., et al. (2018). NCAR release of CAM-SE in CESM2.0: A reformulation of the spectral element dynamical core in dry-mass vertical coordinates with comprehensive treatment of global model simulations. *Geophysical Research Letters*, 45, 10,445–10,453. https://doi.org/10.1002/2017MS001227

Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica*, 13(3), 245–259.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, W. Z., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, 319(5863), 573–574. https://doi.org/10.1126/science.1159315

Murakami, H. (2014). Tropical cyclones in reanalysis data sets. *Geophysical Research Letters*, 41, 2133–2141. https://doi.org/10.1002/2014GL061428

Neiman, P. J., Oakley, N. S., Wick, G. A., Lundquist, J. D., & Dettlinger, M. D. (2008). Meteorological characteristics and landfall precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations. *Journal of Hydrometeorology*, 9(11), 4185–4208. https://doi.org/10.1175/jhm-9-4185.1

Newell, R. E., Newell, N. E., Zhu, Y., & Scott, C. (1992). Tropospheric rivers?—A pilot study. *Geophysical Research Letters*, 19(24), 2401–2404. https://doi.org/10.1029/92GL02916

O’Brien, T. A., Riser, M. D., Loring, B., Elbashandy, A. A., Krishnan, H., Johnson, J., et al. (2020). Detection of atmospheric rivers with inline uncertainty quantification: TECA-BARD v1.0. *Geoscientific Model Development Discussions*, 2020–1–20. https://doi.org/10.5194/gmd-2020-55

O’Gorman, P. A., & Schneider, T. (2009). The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proceedings of the National Academy of Sciences*, 106(35), 14,773–14,777. https://doi.org/10.1073/pnas.0907610106

O’Hare, N. S., Lancaster, J. T., Hatchett, B. J., Stock, J., Walsh, J. F., & Lu, J. (2018). A 22-year climatology of cool season hourly precipitation thresholds conducive to shallow landslides in California. *Earth Interactions*, 22(14), 1–35. https://doi.org/10.1175/El-D-17-0029.1

Payne, A. E., Demory, M.-E., Leung, L. R., Ramos, A. M., Shields, C. A., Rutz, J. J., et al. (2020). Responses and impacts of atmospheric rivers to climate change. *Nature Reviews Earth & Environment*, 1, 143–157. https://doi.org/10.1038/s43017-020-0030-5

Payne, A. E., & Magnusdottir, G. (2014). Dynamics of landfalling atmospheric rivers over the North Pacific in 30 years of MERRA reanalysis. *Journal of Climate*, 27(18), 7133–7150. https://doi.org/10.1175/JCLI-D-14-0034.1
Waliser, D. E., Moncrieff, M. W., Burridge, D., Fink, A. H., Goswami, B. N., et al. (2012). The “Year” of tropical convection (May 2008 April 2010): Climate variability and weather highlights. Bulletin of the American Meteorological Society, 93(8), 1189–1218. https://doi.org/10.1175/2011BAMS3095.1

Wang, S.-Y. S., Huang, W.-R., & Yoon, J.-H. (2015). The North American winter dipole and extremes activity: A CMIP5 assessment. Atmospheric Science Letters, 16(3), 338–345. https://doi.org/10.1002/asl2.565

Wang, M., & Ullrich, P. (2018). Marine Air Penetration in California's Central Valley: Meteorological drivers and the impact of climate change. Journal of Applied Meteorology and Climatology, 57(1), 137–154. https://doi.org/10.1175/JAMC-D-17-0089.1

Wang, S.-Y. S., Yoon, J.-H., Becker, E., & Gillies, R. (2017). California from drought to deluge. Nature Climate Change, 7(7), 465. https://doi.org/10.1038/nclimate3330

Warner, M. D., Mass, C. F., & Salath, E. P. (2015). Changes in winter atmospheric rivers along the North American West Coast in CMIP5 climate models. Journal of Hydrometeorology, 16(1), 118–128. https://doi.org/10.1175/JHM-D-14-0080.1

Wehner, M. F., Reed, K. A., Li, F., Prabhat, Bacmeister, J., Chen, C.-T., et al. (2014). The effect of horizontal resolution on simulation quality in the Community Atmospheric Model, CAM5.1. Journal of Advances in Modeling Earth Systems, 6, 980–997. https://doi.org/10.1002/2013MS000276

White, A. B., Moore, B. J., Gottas, D. J., & Neiman, P. J. (2019). Winter storm conditions leading to excessive runoff above California’s Oroville Dam during January and February 2017. Bulletin of the American Meteorological Society, 100(1), 55–70. https://doi.org/10.1175/BAMS-D-18-0091.1

Wu, C., Liu, X., Lin, Z., Rhoades, A. M., Ullrich, P. A., Zarzycki, C. M., et al. (2017). Exploring a variable-resolution approach for simulating regional climate in the rocky mountain region using the VR-CESM. Journal of Geophysical Research: Atmospheres, 122, 10,939–10,965. https://doi.org/10.1002/2017JD027008

Xu, Z., Rhoades, A. M., Johansen, H., Ullrich, P. A., & Collins, W. D. (2018). An intercomparison of GCM and RCM dynamical downscaling for characterizing the hydroclimatolgy of California and Nevada. Journal of Hydrometeorology, 19(9), 1485–1506. https://doi.org/10.1175/JHM-D-17-0181.1

Zarzycki, C. M., Jablonowski, C., & Taylor, M. A. (2014). Using variable-resolution meshes to model tropical cyclones in the community atmosphere model, Monthly Weather Review, 142(3), 1221–1239. https://doi.org/10.1175/MWR-D-13-00179.1

Zarzycki, C. M., & Ullrich, P. A. (2017). Assessing sensitivities in algorithmic detection of tropical cyclones in climate data. Geophysical Research Letters, 44, 1141–1149. https://doi.org/10.1002/2016GL071606