Weather Patterns Driving Atmospheric Rivers, Santa Ana Winds, Floods, and Wildfires During California Winters Provide Evidence for Increasing Fire Risk

Kristen Guirguis (✉ kguirguis@ucsd.edu)

University of California San Diego Scripps Institution of Oceanography <https://orcid.org/0000-0002-5274-0225>

Alexander Gershunov

University of California San Diego Scripps Institution of Oceanography

Benjamin Hatchett

Desert Research Institute

Tamara Shulgina

University of California San Diego Scripps Institution of Oceanography

Michael J. DeFlorio

University of California San Diego Scripps Institution of Oceanography

Aneesh C. Subramanian

University of Colorado Boulder

Janin Guzman-Morales

University of California San Diego Scripps Institution of Oceanography

Rosana Aguilera

University of California San Diego Scripps Institution of Oceanography

Rachel Clemesha

University of California San Diego Scripps Institution of Oceanography

Thomas W. Corringham

University of California San Diego Scripps Institution of Oceanography

Luca Delle Monache

University of California San Diego Scripps Institution of Oceanography

David Reynolds

University of Colorado Boulder

Alex Tardy

NOAA NWS: NOAA National Weather Service

Ivory Small

NOAA NWS: NOAA National Weather Service

Fred Martin Ralph

University of California San Diego Scripps Institution of Oceanography

Research Article

Keywords: wildfires, atmospheric circulation patterns, natural hazard, historical floods.

Posted Date: September 20th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-887885/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Floods caused by atmospheric rivers and wildfires fanned by Santa Ana winds are common occurrences in California with devastating societal impacts. Planning for these types of events is critical to protect life and property, and extending the lead-times of predictability for these types of events improves emergency response. A better understanding of linkages between large-scale atmospheric circulation patterns and extreme weather represents an important step towards improving predictability and preparedness on subseasonal-to-seasonal (S2S) timescales and for climate change adaptation. In this work, we show that winter weather variability in California, including the occurrence of extreme and impactful events, is linked to four atmospheric circulation regimes over the North Pacific Ocean previously named and identified as the “NP4 modes”. These modes interact on daily timescales to produce recurring winter weather patterns that are major drivers of atmospheric river landfalls, Santa Ana winds, floods, and wildfires. Many recent California natural hazard events resulted from compounding and cascading extremes including frequent atmospheric river landfalls (wet, fuel-producing years) or lack thereof (drought) and followed by Santa Ana-driven wildfires that render the landscape susceptible to hydrologic hazards posed by short-duration high-intensity precipitation events. This historical perspective of atmospheric circulation and impacts over 70 years reveals that weather patterns are changing in a way that enhances wildfire risk in California, while the frequency of weather patterns linked to historical floods is not diminishing. These changes highlight the rising hazards of compounding weather extremes in California’s present and future.

1. Introduction

Extreme winter weather variability in California is largely driven by the interplay between atmospheric rivers and downslope winds (Santa Ana winds (SAWs) in Southern California or Diablo winds in Northern California). Atmospheric rivers (ARs) are narrow filaments of concentrated atmospheric water vapor that can bring extreme precipitation during fall and winter. While critical for California’s water supply, ARs are also the major cause of historical floods (Ralph et al. 2006, 2011; Corringham et al. 2019). Downslope SAWs and their northern counterpart, the Diablo winds, are characteristically hot, dry, offshore winds that bring fire weather to coastal and inland California (Abatzoglou et al. 2021). Typically, the SAW season begins in fall and peaks in December (Guzman-Morales 2016) whereas Diablo winds peak during October (Bowers 2018). SAWs are linked with Southern California’s most destructive wildfires (Westerling et al. 2004; Kolden et al. 2018; Gershunov et al. 2021) while Diablo winds have been involved with many recent major Northern California fires (e.g., Nauslar et al. 2017; Smith et al. 2018; Mass 2021). The timing of offshore winds relative to ARs is an important factor for hazardous wildfires in California, where the risk of wildfire is enhanced if a strong SAW or Diablo occurs before the first seasonal rain when fuel moisture is climatologically low. ARs and downslope winds are driven by certain recurring weather patterns over and offshore of western North America that favor onshore or offshore flow over California, respectively (e.g. Ralph et al. 2004; Neiman et al 2008; Guirguis et al. 2018; Hughes and Hall 2010; Abatzoglou et al. 2013; Guzman-Morales et al. 2016).

Previous studies have demonstrated the importance of certain atmospheric circulation patterns in driving AR landfalls over California and western North America. AR landfalls are often associated with a ridge situated over/near Alaska ($\sim 160^\circ\text{W}$) with a trough to the southeast and a strong pressure gradient that channels marine moisture toward the coast (e.g. Weaver 1962; Strobino and Reynolds 1995; Ralph et al. 2004; Neiman et al. 2008; Guirguis et al. 2018, 2019, 2020). The position, strength, and orientation of these circulation features relative to coastal topography modulate the landfall location as well as the amount and spatial distribution of moisture transport and precipitation (Neiman et al. 2008; Mundhenk et al. 2016; Swales et al. 2016; Hecht and Cordiera 2017; Hu et al. 2017; Guirguis et al. 2019), which is mainly orographic. ARs have also been linked to extratropical cyclones and closed low pressure systems (Oakley et al. 2017; Zhang et al. 2019).

SAWs are associated with anomalous surface high pressure centered over the interior Great Basin driving anticyclonic flow through complex terrain bringing strong, dry easterly/northeasterly downslope winds to Southern California (Hughes and Hall 2010; Abatzoglou et al. 2013; Guzman-Morales et al. 2016). These winds warm by adiabatic compression as they travel from the elevated Great Basin and over the 3000 m high Transverse and Peninsular Ranges down to the coast. Thus, SAWs are often associated with coastal heat waves in the fall, winter and spring (Gershunov et al. 2021). These hot, dry, and windy conditions present substantial fire risk to California when vegetation is dry. Harmful health impacts associated with SAW-driven heat waves (Schwartz et al. 2020) and wildfire smoke (Aguilera et al. 2020, 2021a,b) have also been reported. While all SAWs warm adiabatically, they do not always produce heat waves at the coast. Hot and cold SAWs result from distinctly different synoptic dynamics and Great Basin land surface conditions (Gershunov et al. 2021). All SAWs involve a surface high pressure over the northeastern Great Basin, which develops in association with a blocking high aloft in the case of hot SAWs, and with Rossby wave breaking in the wake of transient cold frontal cyclones in the case of cold SAWs; the latter are also associated with anomalous Great Basin snow cover (Gershunov et al. 2021). Southern California wildfires are preferentially spread by hot SAWs (Gershunov et al. 2021).

Typically, the interplay between ARs, SAWs, extreme precipitation, and wildfires is thought of as a situation where one extreme (ARs) is the remedy or prevention of the other extreme (wildfires). However, when ARs occur following wildfires, they can cause deadly debris flows over the burn area if short-duration, high intensity rainfall occurs during cold frontal passage (Oakley et al. 2018), compounding the original impacts. Here, we show that ARs and SAWs are more closely linked than previously discovered through interacting synoptic-scale atmospheric circulation regimes. Specifically, we demonstrate how four key circulation regimes over the North Pacific Ocean (“North Pacific Modes” or “NP4 modes”), identified and described in previous work (Guirguis et al. 2020, hereinafter GGR’20), interact on daily timescales to produce recurring, regionally-important weather patterns responsible for impactful weather in California and along the West Coast. These four circulation regimes (shown in Fig. 1a) are known as the Baja-Pacific (BP), Alaskan-Pacific (AP) Canadian-Pacific (CP), and Offshore-California (OC) modes. The NP4 modes share characteristics with established, well-known teleconnections identified in previous work. For example, the Alaskan-Pacific and Canadian-Pacific modes are related to the well-known West Pacific Oscillation (WPO) and Pacific North American (PNA) Pattern, respectively (GGR’20), which were

first identified in Barnston and Livezey (1987). Other studies aiming to identify circulation regimes over this region have found similar patterns (e.g. Straus et al. 2007, Amini et al. 2019; Gibson et al. 2020).

The NP4 modes represent four winter teleconnections identified by the preferred position of atmospheric ridges and troughs over the North Pacific Ocean and along the West Coast. As these modes oscillate over this region, they can shift in- or out-of-phase with each other on a given day, and seasonally they exhibit a strong tendency to persist in one phase over the other (GGR'20). The joint phase combination of the NP4 modes has been shown to strongly modulate coastal water vapor transport, AR landfalls, and California precipitation, and has been linked to historical floods (GGR'20). In this study, we extend the relevance of the NP4 mode interactions to other types of extreme weather events and their consequences, including SAWs and historical wildfires, and show how these interactions produce distinct weather patterns that recur throughout the historical record. We focus mostly on the interplay between ARs and SAWs (and associated floods and wildfires), but also discuss heat waves, cold extremes, and snowpack accumulation.

It is well-recognized that the interactions between large-scale teleconnections play an important role in modulating extreme weather in the western US. For example, previous work has focused on the different phase combinations of El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), PNA, EPO, West Pacific Index (WPO), Arctic Oscillation (AO), Quasi-Biennial oscillation (QBO), Madden-Julian Oscillation (MJO), etc. (e.g. Gershunov and Barnett 1998, Gershunov and Cayan, 2003; Guan et al. 2013; Guan and Waliser 2015; Wise et al. 2015; Mudhenk et al. 2016, 2018; DeFlorio et al. 2018; Guirguis et al. 2019, and many others). In this work we consider phase-relationships between a specific set of circulation regimes, the NP4, known to be important in this region (GGR'20).

We first classify and describe the dominant, recurring weather patterns impacting California and the western US (Sect. 3). We then identify those weather patterns associated with ARs, extreme precipitation, and historical floods (Sect. 4) and those associated with Santa Ana winds and wildfires (Sect. 5). In Sect. 6, we diagnose and explain observed trends in weather pattern frequency and discuss the implications for wildfire risk and water resources. We discuss the timescales of persistence and relevance for S2S predictability in Sect. 7. Finally, we provide a summary and discuss the implications for resource and emergency management, S2S forecasting, and climate change (Sect. 8).

2. Data And Methods

2.1. Time period of study

Our time period of study spans 1949–2021. However, some variables have shorter records due to data availability. The season of focus is extended winter (November-February; hereafter winter) to coincide with the NP4 dataset (described in Sect. 2.8), and which is also the part of the season most active with respect to both AR activity and SAW activity in California (Gershunov et al. 2017, and Guzman-Morales and Gershunov 2019, respectively).

2.2. Atmospheric Variables

Daily 500 mb geopotential height (Z500) and wind fields for the period spanning Nov-Feb 1949–2021 are from NCEP/NCAR 2.5° global reanalysis (Kalnay et al. 1996). Daily anomalies were calculated relative to the annual/semiannual seasonal cycle fit using least squares regression.

2.3. Atmospheric River Detection and AR Intensity Scale

The SIO-R1 catalog of Gershunov et al. (2017) is used to identify landfalling ARs along the coast of western North America. The detection method uses threshold criteria for integrated water vapor (IWV > 15 mm) and integrated vapor transport (IVT > 250 kg m⁻¹s⁻¹) to identify elongated objects of high moisture content that intersect the coast. The AR scale of Ralph et al. (2019) is used to categorize the magnitude of storms. This 5-scale classification is based on IVT magnitude and duration where the scale 1–5 describes ARs as weak, moderate, strong, extreme, and exceptional, respectively. AR scales 1–2 are mostly beneficial providing needed precipitation without damage, whereas AR scales 4–5 are mostly hazardous with peak IVT in the range of 750 to more than 1250 kg m⁻¹s⁻¹. Flood damages in the western U.S. increase exponentially with the AR scale (Corringham et al. 2019). The SIO-RI AR catalog is available at <https://weclima.ucsd.edu/data-products/>.

2.4. Santa Ana Winds

Historical SAW events are identified using the daily Santa Ana Winds Regional Index (SAWRI) of Guzman-Morales (2016, 2019). This data product is based on 65 years of hourly data from the dynamically downscaled CaRD10 dataset (Kanamitsu and Kanamaru, 2007) and validated against station observations. SAWs are defined by strong, sustained, northerly to easterly winds (Guzman-Morales et al., 2016). This study uses the updated daily version of the Guzman-Morales and Gershunov (2019) SAW index, regionalized over Southern California (~ 32–35 °N, 116–118 °W) and available at <https://weclima.ucsd.edu/data-products/>. We define moderate (extreme) SAWs as those exceeding the 50th (90th) percentile.

2.5. Historical Temperature and Precipitation

Daily precipitation and maximum temperature (Tmax) data are from Livneh et al. (2013, 2015), which is a gridded data product available at a 1/16° spatial resolution over the period 1950–2015 (available at <https://climatedataguide.ucar.edu/climate-data>). The source data are from approximately 20,000 stations in the Global Historical Climatology Network (GHCN). Extreme precipitation is defined as daily accumulation above the 95th percentile. Heat waves (cold extremes) are defined following Gershunov and Guirguis (2012) as daily temperatures persisting for at least one day above the 95th (below the 5th) percentile after removing the seasonal cycle.

2.6. Sierra Nevada Snowpack

We use monthly snow water equivalent data from a single snow course in the Northern Sierra Nevada. Specifically, we selected Donner Summit (39.3 °N, -120.3 °W, elevation 2100 meters, station ID 20K10) from the Natural Resources Conservation Service (<https://wcc.sc.egov.usda.gov/nwcc/rgrpt?report=snowcourse&state=CA>). This location sits at the intersection of three key headwater regions (Yuba, Truckee, and American Rivers) involved in managing California and Nevada water resources. The Donner Summit snow course has a long (1913–2021) and complete record.

2.7. Wildfire

Wildfire information is from the California Fire Protection's Fire and Resource Assessment Program (FRAP) fire perimeters database (<https://frap.fire.ca.gov/frap-projects/fire-perimeters/>). We focus on fire start dates for historical wildfires with burn sizes exceeding 1000 acres in the Southern California (SoCal) counties of Santa Barbara, Ventura, Los Angeles, Orange, Riverside, San Bernardino, and San Diego. Our sample includes 76 wildfires spanning 1949–2018, with most occurring in November ($n = 40$) or December ($n = 21$). It is worth noting that most wildfires in California occur in October, which is outside of our extended winter focus season. However, the wildfire season can and does extend into winter during drought years or when delayed rains extend dry vegetation into the peak of SAW season.

2.8. North Pacific Atmospheric Circulation Regimes

We use daily amplitudes of four North Pacific atmospheric circulation regimes (NP4 modes), which were identified and shown to be essential drivers of vapor transport and AR activity along the coast of western North America by Guirguis et al. (2018, hereinafter GGR'18) and GGR'20. These four modes are named according to their geographic centers of action: Baja-Pacific (BP), Alaskan-Pacific (AP), Canadian-Pacific (CP), and Offshore-California (OC) modes. The NP4 modes were identified using rotated Empirical Orthogonal Function (EOF) analysis applied to Z500 anomaly fields over a large domain spanning the northern Pacific Ocean and western North America. While the NP4 modes are not the most important in terms of field variance (i.e., they correspond to higher-order rotated principal components), they were found to be the most important modes for coastal vapor transport, AR landfalls, and extreme precipitation in California (GGR'18, GGR'20). The EOF loading patterns (maps) associated with the positive phase of each mode are shown in Fig. 1a. The portion of the domain where these modes are most influential is shown in Figs. 1b and 1c. Specifically, Fig. 1b shows the locations where one of the four modes is by itself responsible for more than 50% of the Z500 variance. Figure 1c shows the collective influence of the four modes, where we see that together these modes explain 25–90% variance in the portion of the domain most relevant for west coast weather. The NP4 dataset used in this study is described in Guirguis et al. (2020b) and is available at <https://doi.org/10.6075/J0154FJJ>.

2.9. Weather regime Classification

Daily weather regimes are classified based on the joint phase combination of the NP4 modes. As the NP4 modes oscillate over the North Pacific, their daily interactions determine the position and strength of ridges and troughs along the coast of western North America. Unique NP4 phase combinations result in

distinct weather patterns that drive extreme weather in California (GGR'18 GGR'20). On a given day, each of the four NP4 modes can be positive or negative, which yields 16 possible phase combinations, and 16 corresponding weather regimes (introduced and described in Sect. 3).

We use the terminology “weather pattern” and “weather regime” somewhat interchangeably. “Weather pattern” is taken to mean the Z500 anomaly field itself while “weather regime” refers to the classification of that pattern. A catalog of historical weather regimes observed over 1949–2021 is developed as an accompaniment to this publication and is available at <https://weclima.ucsd.edu/data-products>.

3. Winter Weather Patterns Impacting The West Coast

Figure 2 shows Z500 anomaly patterns associated with the sixteen different phase combinations of the NP4 modes, which are used to define winter weather regimes (WR) impacting the West Coast. We first provide examples of how the NP4 modes interact to create distinct weather patterns (Sect. 3.1) and then provide an overview of circulation characteristics and impacts associated with each weather regime (Sect. 3.2).

3.1 How the NP4 modes interact to produce distinct weather patterns

Examples of how the NP4 modes interact to produce distinct weather patterns are provided in Fig. 3 and Fig. 4 for 2016–2017 (a wet year) and 2020–2021 (a dry year), respectively (e.g. Abatzoglou et al. 2017, <https://wrcc.dri.edu/wwdt/>).

Figure 3 shows the daily NP4 amplitudes (Fig. 3a) and daily interactions (Fig. 3b) for water year 2016–2017 (WY2017). We highlight three events (December 7–16, January 3–11, and February 1–8) when the NP4 modes exhibited the same joint phase configuration (labeled E1, E2, and E3; Fig. 3). Specifically, during these three events the BP mode was positive (which favors a ridge over Baja California, c.f. Figure 1a), the AP mode was negative (favoring high pressure over Alaska), and the OC and CP modes were negative (favoring low pressure over western Canada and offshore from California, respectively). This mode configuration results in the atmospheric circulation and IVT patterns shown in Figs. 3c and 3d, respectively. This type of pattern (classified as WR10, see Fig. 2) is associated with strong onshore flow, AR landfalls, and wet conditions over Central and Southern California with heavy precipitation over the Sierra Nevada. In this example, the February 1–8 event highlights the Oroville Dam crisis (Vahedifard et al. 2017) that resulted in the evacuation of over 180,000 people due to spillway damage from extreme runoff during intense and prolonged AR precipitation with high snow levels causing rain-on-snow. These three events also produced flooding on the leeward side of the Sierra Nevada (Sterle et al. 2019).

The second example is for WY 2021 (Fig. 4). Here we highlight three different events (November 1–4, November 27–December 8, and January 9–17) sharing a common NP4 phase combination. For these events (labeled E4–E6), the BP and AP modes were positive (favoring a ridge over Baja California and a trough over Alaska, respectively, c.f. Figure 1a) and the CP and OC modes were negative (favoring high pressure over western Canada and offshore California, respectively). This combination results in the

atmospheric circulation (Fig. 4c) and IVT patterns (Fig. 4d), featuring anomalous onshore flow over British Columbia/Pacific Northwest and offshore flow over Southern California. This pattern of circulation (classified as WR5, see Fig. 2) is associated with ARs in the northern latitudes and SAW conditions over Southern California. The two longer events (E5 and E6) prompted Red Flag Warnings in Southern California along with large-scale public safety power shutoffs initiated by electric companies to prevent accidental ignitions by utility equipment (Murphy, 2019; Chediak and Sullivan 2021).

3.2. Impacts and circulation characteristics associated with each weather regime

Impacts associated with each weather regime are shown in Fig. 5 for AR landfall probabilities (a), precipitation anomalies (b), probability of extreme precipitation (c), and percent of total historical precipitation (d). Additional impacts are shown in Fig. 6 for SAW probabilities (a), temperature anomalies (b), heat wave probabilities (c), and cold extreme probabilities (d). The specific NP4 phase combination associated with each weather regime is shown in Figure S1 and is also displayed as highlighted text in the lower left of each map in Fig. 2. For all weather regimes shown in Fig. 2, the salient ridge/trough features are well represented by the vast majority of days within each weather regime class. For example, Figure S2 shows the percent agreement among days within each sample in the sign of the Z500 anomaly, which reaches 94–100% for ridge/trough positions at the point of maximum overlap.

Weather regimes 1–6 feature a strong ridge positioned over/offshore western North America (Fig. 2), creating atmospheric blocking conditions that produce dry weather over much of the western US, especially California (Fig. 5b-d). Offshore flow occurs over Southern California along the eastern boundary of the ridge, bringing elevated chances of SAW conditions (Fig. 6a). Four of these patterns (WR1, WR4, WR5 and WR6) favor warm temperatures, with an elevated chance of heat wave occurrence, whereas two patterns (WR2&WR3) bring cold conditions (Figs. 6b-d). These warm and cold flavors of SAWs are consistent with Gershunov et al. (2021). In the northern latitudes, WR 2–6 result in enhanced onshore flow along the northern/northwestern boundary of the ridge, bringing elevated AR probabilities for British Columbia and the Pacific Northwest (Fig. 5a).

Weather regimes 7–12 bring wetter conditions to the western US coast (Fig. 5) due to the position of an offshore trough that enhances transport of oceanic moisture over land (Fig. 2). Weather regimes 7–8 feature a trough positioned near the Pacific Northwest coastline. The location of this trough is favorable to precipitation and AR landfalls over Oregon and Washington and into Northern California. Weather regimes 9–10 feature a trough offshore California, which brings precipitation and AR landfalls over Central and Northern California. For weather regimes 11–12, the trough is further equatorward, favoring a more southerly AR track with wet conditions centered over Southern California and penetrating into the interior Southwest.

Weather regimes 15–16 bring anomalous onshore flow over Baja California (Fig. 2), with wet conditions into the Sonoran Desert region (Fig. 5). Concurrently, these weather patterns bring strong easterly/northeasterly flow to Northern California/Pacific Northwest along the eastern boundary of a ridge posited over Alaska or British Columbia. Previous work has noted the link between ARs over Baja

and inland penetration of moisture into the Desert Southwest (Rutz et al., 2012, 2014, 2015; Swales et al. 2016; Gershunov et al. 2017).

4. Atmospheric Rivers, Extreme Precipitation, And California Water Resources

The weather regimes responsible for most of California's total and extreme precipitation are WR9-12 (Fig. 5c-d). WR9 is characterized by a deep and expansive trough centered over the Gulf of Alaska, with a ridge positioned over Southern California that helps to channel moisture towards Central and Northern California (Fig. 2). This weather pattern elevates AR probability 3-fold along the coast from Central California to the Pacific Northwest (Fig. 5a) and brings a high probability of extreme precipitation (Fig. 5c). In Central and Northern California, by contributing upwards of 30% of annual precipitation, WR9 is the most important source of precipitation (Fig. 5d). WR10 is also vital for California water resources (Fig. 5d) and is an important driver of AR landfalls (Fig. 5a) and extreme precipitation (Fig. 5c). It is similar to WR9 in the position of the high and low pressure centers along the West Coast (Fig. 2). However, WR10 is characterized by a ridge over Alaska (negative phase of the Alaska-Pacific Mode) and a positively tilted trough that extends towards the tropics.

WR12 is similar to WR10, except it lacks the ridge over Southern California, which is an important distinction as its absence allows the trough to expand equatorward (Fig. 2) bringing more AR activity and precipitation to Southern California (Fig. 5). WR11 is also impactful for Southern California, bringing a high probability of extreme precipitation when it occurs (Fig. 5c), but it accounts for a smaller proportion of total SoCal precipitation (Fig. 5d) due to the lower frequency of occurrence (i.e., WR11 is more transitory and is observed on 2% of days compared to 9% for WR12).

Figure 7 summarizes just how critical these weather patterns are to California precipitation extremes and water resources. Collectively, while they account for only 25% of November-February days, they account for up to 72% of total precipitation and up to 80% of extreme precipitation for some locations in California (Fig. 7a-b). Using the AR intensity scale of Ralph et al. (2019), we find that WR9 and WR10 are the primary synoptic weather patterns for the most intense and destructive ARs (AR scale 4&5, Fig. 7c). WR9 and WR10 collectively account for approximately 50% of AR category 4 storms and more than 80% of AR category 5 storms impacting California. Median flood damages associated with AR category 4 and 5 events are on the order of \$20 million and \$260 million, respectively (Corringham et al. 2019).

Previous work has shown how the presence or absence of one-to-three intense storms can make-or-break a water year (Dettinger 2011) or terminate a drought (Dettinger 2013), or prevent the onset of a megadrought (Hatchett et al. 2016). Our findings suggest that these make-or-break storms most likely carry synoptic signatures similar to WR9-12. These few but large storms are important in building the Sierra Nevada snowpack that later melts and provides beneficial warm season water resources to meet human and ecological demands. Figure 8 shows the relationship between the seasonal frequency of WR9-12 and interannual snowpack variability in the Northern Sierra Nevada, which demonstrates a very

strong relationship between the number of days in a season that WR 9–12 were present and snow water equivalent (SWE) at Donner Summit on March 1. The relationship is strong ($p < 0.001$, $r = 0.61$) even though important details including precipitation itself or snowmelt events are not considered.

4.1. Historic California Floods

We selected eight flood events to investigate from a weather regime perspective. These historic events were selected because they have achieved notoriety for the amount of destruction they caused. These are the floods of December 1955, December 1964, January 1969, February 1986, January 1995, December/January 1996-97, February 2017, and February 2019.

Figure 9 shows the IVT magnitude during AR landfalls at different latitudes along the coast during Nov-Feb for the eight seasons when these floods occurred, classified by weather regime. For California latitudes (32.3–42 °N) we see that the most intense ARs, including the historic floods (labeled F1-F8), are associated with WR9 and WR10 (See also Fig. 5). Often, the historic floods follow on the tails of one or more ARs, which prime the soil moisture, groundwater, and streamflow conditions for subsequent flooding (Albano et al. 2020). Evidence of “AR Families”, as defined by Fish et al. (2020), whereby successive AR landfalls occur at the same location, are also seen (e.g. repeated ARs hitting California during 1996-97 and 2016-17 classified as WR9/10). Such “AR Families” impacting California have been linked to certain semi-stationary atmospheric circulation patterns over the North Pacific (Fish et al. 2020), which are similar in their ridge/trough positions to WR9-12.

Figure 10 shows Z500 anomalies on the peak day of each event along with the weather regime classification, where we see that all peak days are classified as either WR9 or WR10. These patterns favor very strong vapor transport over California (Fig. 11). While the patterns are similar, there are distinctions in the position of the ridge located over/near Alaska and the position/orientation of the trough relative to the coast. The positioning of these synoptic features modulates the location of the AR track as it intersects the coast, which is critical from a local impacts perspective (e.g. note the latitudinal differences in the AR landfall location in Fig. 11). While there are slight variations in the synoptic signatures, the weather patterns represent a recurring type of atmospheric circulation linked to extreme precipitation in California, which is consistent with many studies in the literature investigating these or other extreme AR events (e.g. Weaver 1962; Baker 1994; Baker and Estes 1994, Strobins and Reynolds 1995; Ralph et al. 2004; Nieman et al. 2008; Guirguis et al. 2018, 2019, 2020; Hatchett et al. 2020), including hypothetical cases (Porter et al. 2011).

5. Santa Ana Winds And Fire Weather

We next investigate the role of the sixteen weather patterns in driving the opposite regional weather phenomena: Santa Ana winds and wildfire. Wildfires in California are of increasing concern as recent years have brought extremely destructive and widespread wildfires with devastating loss of life and property and long periods of unhealthy air quality. The largest Southern California wildfires are typically

associated with anomalously hot temperatures, dry vegetation, and persistent Santa Ana winds. Here we discuss the types of weather patterns most conducive to wildfire in California during winter.

Weather regimes 1–6 all support offshore flow over Southern California (Fig. 2) and SAW probabilities in the range of 39–65%, or 20%–100% above average (Fig. 6a). These six patterns are also anomalously dry for California generally (Fig. 5), although WR6 can produce AR impacts in Northern California (Fig. 5a) in cases when the offshore trough (Fig. 2) moves closer to shore.

Two of these patterns are associated with cold SAWs (WR2&3), and the rest are hot SAW patterns with elevated chances of a heat wave (Fig. 6). Hot SAWs are associated with a ridge centered over the Great Basin, while cold SAWs feature a trough over the interior Southwest and a positively tilted offshore ridge that brings northeasterly flow to coastal California (Figure S3). The synoptic signatures associated with hot and cold flavors of SAWs are consistent with recent findings (Gershunov et al. 2021).

Figure 12 shows the weather regime distribution for start dates of the largest Southern California wildfires. As expected, the weather regimes associated with SAWs (WR1–6) are those responsible for most (78%) large wildfire starts, and the hot SAW patterns are responsible for more than twice as many starts (58%) as cold SAWs (24%). Gershunov et al. (2021) found hot SAWs to be responsible for the largest wildfire acreages burned in Southern California, partly because hot SAWs tend to last longer, high temperatures support enhanced drying of vegetation and lower relative humidity, but also because cold SAWs tend to be preceded by precipitation. Weather regime 5 is associated with the largest number of wildfire ignitions (30%), which results from strong offshore flow (Fig. 2) favoring fire weather: hot, dry, SAW conditions (Figs. 5&6). The WR5 pattern also occurs more frequently than other hot, dry, SAW patterns (i.e. WR5 occurs on 10% of days compared to 3% for each WR1 and WR4). Composites of atmospheric circulation associated with Southern California wildfire start days classified as WR1–6 (Figure S4) highlight the similarity between synoptic circulation on specific wildfire start days and the defined weather regimes (Fig. 2).

5.1. The California Thomas Fire of 2017

In addition to hot, dry, and windy conditions needed for a wildfire to grow, the largest wildfires are associated with the persistence of these conditions over a period of time without rain. The Thomas Fire of 2017–2018 burned for over a month, igniting December 4 before being fully contained on January 12. Figure 13a shows atmospheric river activity during 2017–2018, highlighting ARs hitting land between 22.5–57.7 °N. We see that AR landfalls occurred along the West Coast in November of 2017 (seen as green circles mostly north of 35°), but these storms primarily impacted the Pacific Northwest and Northern California, while Southern and Central California remained dry. December is typically the most active month for ARs in Northern California and the second most active month for ARs in Southern California (Gershunov et al. 2017). However, in December 2017 no ARs made landfall in the State. Following ignitions by downed power lines on and around December 4, the dominant weather patterns were those associated with hot, dry, SAW conditions. From Fig. 13b, the most common weather regimes during December 4–January 12 were WR1 (11 days), WR4 (6 days), WR5 (6 days), and WR6 (5 days).

Containment of the fire was aided by a weak atmospheric river on January 9–10 (classified as WR8, Fig. 13a). While this storm finally brought rainfall, it also brought tragedy as it included short-duration, high intensity precipitation associated with cold frontal passage that triggered fatal post-fire debris flows in the coastal community of Montecito (Oakley et al. 2018).

6. Observed Trends In Weather Regime Frequency And Implications For California Water Resources And Fire Risk

In the past decade, California has endured two extreme and persistent droughts, ongoing extreme heat, and eight of the ten largest wildfires in over a century of records (Krishnakumar and Kannan 2020). Here, we investigate if and how winter weather patterns are changing across the western US, and how these changes might affect winter weather variability and extremes in California. Figure 14 gives the seasonal frequency of each weather regime over the historical record, along with statistically significant ($p < 0.05$) increasing (red) and decreasing (blue) trends. The weather patterns found to be increasing in frequency are WR1, WR4, WR5, and WR7. While WR7 is not linked to extreme California weather in our analysis, the other three weather regimes (1, 4 & 5) are major contributors to historical wildfires (Fig. 12 and Fig. 13b) and are associated with heat waves in California and the western US (Fig. 6c). The combined seasonal frequency of these three weather regimes is provided in Fig. 15b, which shows a strong increase in the frequency of these impactful weather patterns (slope = 0.21% per year, $p < 0.001$). During the 2021 water year, which was the second driest statewide in 125 years (WRCC 2021), these weather patterns accounted for 41% of days in the season. This anomaly was exceeded only once previously in 2015, also a critically dry year in California and Nevada (Sterle et al. 2019; WRCC 2021).

Along with increasing fire risk due to the rising frequency of hot, dry, SAW patterns, we also find evidence of decreasing frequency of weather patterns associated with cold SAWs (WR3; see also Gershunov et al. 2021) and precipitation in the Southwest (WR11, WR12, and WR14). Figure 15a shows the combined frequency of the patterns associated with southwest precipitation (WR11, WR12, and WR14, slope=-0.18% per year, $p < 0.001$). These are all associated with a deep trough over and offshore from western North America (Fig. 2) with moisture transport along a southern track bringing precipitation to Southern California and the Desert Southwest (Fig. 5). These weather regimes also tend to be colder (Figs. 6b and 6d), therefore this decreasing trend could mean less precipitation in general, but also less cold precipitation which has implications for snow accumulation and storage. We find no long-term trends for the weather patterns associated with the strongest ARs and the most destructive California floods (WR9 and WR10). This suggests that atmospheric circulation is changing to favor fire weather at the expense of precipitation in Southern California, but the risk of extreme precipitation and flooding caused by the strongest ARs is not diminishing.

The observed trends in the frequency of certain weather patterns is related to the rising frequency of ridging over land along the west coast. Specifically, we observe a positive trend in the Baja-Pacific mode, which makes ridging over Baja California more likely, and a negative trend in the Canadian-Pacific mode, which corresponds to an increase in ridging over the Pacific Northwest and western Canada (Figure S5

and Fig. 1a). These geospatial differences in trends of height anomalies over land relative to those over the Pacific Ocean favor atmospheric blocking conditions associated with dry weather in California. Persistent ridging has been implicated in recent California droughts (e.g., Swain et al. 2014; Bond et al. 2015; Gibson et al. 2020).

7. Timescales Of Persistence And Relevance For S2s Predictability

Within a season, the persistence of one or more NP4 modes in one phase or another makes certain weather conditions more or less likely as ridges or troughs persist over and offshore from western North America (c.f. Figure 1a). As the NP4 modes oscillate with different periodicity and come in- and out-of-phase with each other (as seen in Figs. 3a and 4a), the weather regimes transition on relatively short daily timescales (median = 3 days, Figure S6, purple bars). However, the NP4 modes themselves are more persistent, fluctuating on extended-range (10–21 days) to S2S (21–90 days) timescales, and this persistence is modulated by the more slowly-varying climate system (GGR'20). The timescale of persistence of the NP4 modes (number of consecutive days in one phase before transitioning) is on the order of a few days to several weeks (Figure S6, orange lines). Although the median persistence of the NP4 modes over the historical record is 10–13 days, within a given season much longer persistence commonly occurs. For example, Figure S6 (green line) shows the longest-lasting event identified in each season. This shows that during all seasons in the historical record there has been at least one long-duration event where one or more modes persisted in one phase for at least 19 days and up to 62 days before transitioning. During 68% of seasons, such phase persistence has lasted for at least 30 days. This type of persistence makes particular extreme weather hazards more or less likely on timescales up to two months. Additionally, this behavior can determine if California reaches, exceeds, or falls short of achieving normal precipitation in a given water year. On seasonal timescales, it is common for one or more NP4 modes to exist predominantly in one phase or another during a season due to modulation by large-scale teleconnections such as ENSO (GGR'20). Thus, the interaction between large-scale climate forcing and the NP4 modes, and the resulting seasonal weather regime distribution, represents important S2S linkages that should be explored in future research.

8. Discussion

In this study, we demonstrate how four modes of atmospheric circulation over the North Pacific Ocean interact to produce distinct weather patterns that recur throughout the historical record. These recurring weather patterns drive AR landfalls, extreme precipitation, historic floods, Santa Ana winds, wildfires, and temperature extremes during California winters. Relationships between the driving NP4 modes and climate-scale teleconnections like ENSO have already been discovered (GGR'20) and the results presented here suggest important linkages between both seasonal- and weather-scale processes that project onto S2S predictability of the various meteorological phenomena explored in this work. The methodology developed here can easily be applied to dynamical weather forecast models to investigate the predictability of extreme weather impacts at S2S lead times. Predicting the phase of one or more NP4

modes, using dynamical, statistical, or hybrid methods, would be highly useful for situational awareness regarding the likelihood of extreme weather events. Dynamical models have been shown capable of producing skillful forecasts of large-scale circulation features at lead times of 2.5 weeks (e.g. Ferranti et al. 2018, 2019) to several weeks (Gibson et al. 2020b). Additional lead time and higher confidence in long-lead forecasts can be translated by forecasters into improved impact-based decision support (Uccellini and Ten Hoeve 2019) to partner agencies and used to provide earlier warning to public audiences through social media before extreme events (e.g., Lambrecht et al. 2019, 2021).

An important outcome of this work is the generation of a catalog of daily weather patterns spanning 73-years (<https://weclima.ucsd.edu/data-products>), which can be used for monitoring and predictability studies. The methodology offers a perspective on weather pattern transitions not previously explored. In contrast to more traditional methods that use a categorical perspective (e.g., cluster analysis or self-organizing maps), our approach identifies weather patterns as a function of the continuous wave-like atmospheric oscillations that occur in the region of the globe most relevant for California (c.f. Figures 3–4). Our weather regime classification has been shown to be skillful at representing important circulation features associated with impactful events, including destructive floods and Southern California wildfires. Using this approach, we find that the seasonal frequency of weather patterns associated with wildfire is increasing while other patterns that bring precipitation to southern California and the Desert Southwest are decreasing in frequency. This is an unsettling set of trends, as during 2020 California suffered its worst wildfire season on record, causing extensive impacts to ecosystems, property, and public health (e.g. Aguilera et al. 2020, 2021a,b). The continued dry conditions experienced during winter 2020–2021 have further exacerbated already extreme fire hazards and as of this writing, the 2021 fire season is on track surpass the previous year's record in terms of acreage burned.

Importantly, while circulation changes appear to be reducing the likelihood of some types of precipitation events (WR11, WR12, WR14), there is no observed change in the weather patterns responsible for the most intense ARs and destructive floods (WR9 and WR10). With warming due to anthropogenic climate change, these patterns could potentially be even more destructive as the atmosphere can more effectively transport larger quantities of water vapor (Rhoades et al. 2021). This is consistent with recent work focused on precipitation regime changes in California using climate model projections (Polade et al. 2017; Espinoza et al. 2018; Swain et al. 2018; Gershunov et al. 2019), which suggest that future California precipitation will come by way of fewer, more intense storms with longer dry spells in between.

There are many research questions that could be explored using this methodology and data catalog. While we provided only a cursory look at the relationships with snowpack, the role of different weather patterns in driving snow accumulation and depletion throughout the western United States, would be valuable knowledge from a water resource perspective, particularly as snowpack declines continue (Siirila-Woodburn et al. 2021). Further investigation on the timing and transition of different weather patterns could provide insight for S2S predictability. While this analysis focused on the California winter season, the methodology could be applied to other seasons to study warm season heat waves and/or fire weather, as well as to other regions. Improving our understanding of the linkages between climate

change, seasonal-scale teleconnections, and extreme weather will be critical for effective emergency planning, resource management, and climate change adaptation efforts at local, regional, and state levels.

9. Declarations

Funding

This research was funded by the U.S. Department of the Interior via the Bureau of Reclamation (USBR-R15AC00003), the California Department of Water Resources (4600010378 UCOP2-11), and by the Regional Integrated Sciences and Assessments (RISA) California–Nevada Climate Applications Program and the International Research Applications Program of the National Oceanic and Atmospheric Administration (awards NA17OAR4310284 and A18OAR4310341). Additional funding was provided by the University of California Office of the President MRPI grant MRP-17-446315. This study contributes to DOI's Southwest Climate Adaptation Science Center activities and NOAA's California and Nevada Applications Program award NA11OAR43101.

Ethics Declaration

The authors declare no competing interests.

Availability of Data and Material

The weather regimes catalog developed for this study, along with the NP4 dataset, Santa Ana winds regional index, and the SIO-R1 AR catalog are available at <https://weclima.ucsd.edu/data-products/>. The Livneh temperature and precipitation data are available at <https://climatedataguide.ucar.edu/climate-data>. Wildfire information is from the California Fire Protection's Fire and Resource Assessment Program (FRAP) fire perimeters database available at <https://frap.fire.ca.gov/frap-projects/fire-perimeters/>. Snow water equivalent for the Sierra Nevada are from the Natural Resources Conservation Service available at <https://wcc.sc.egov.usda.gov/nwcc/rgrpt?report=snowcourse&state=CA>.

Code Availability

Code developed for this study will be made available upon request

10. References

1. Abatzoglou, J. T., R. Barbero, and N. J. Nauslar, 2013: Diagnosing Santa Ana winds in Southern California with synoptic-scale analysis. *Wea. Forecasting*, 28, 704–710, doi:10.1175/WAF-D-13-00002.1
2. Abatzoglou, J.T., D.J. McEvoy, and K.T. Redmond, 2017: The West Wide Drought Monitoring at Fine Spatial Scales, *BAMS*, 98 (9), 1815-1820.

3. Aguilera, R., T. Corringham, A. Gershunov and T. Benmarhnia, 2021: Wildfire smoke impacts respiratory health much more than fine particles from other sources: observational evidence from Southern California. *Nature Communications*. 12:1493, <https://doi.org/10.1038/s41467-021-21708>.
4. Aguilera, R., K. Hansen, A. Gershunov, S. Ilango, P. Sheridan, and T. Benmarhnia, 2020: Respiratory Hospitalizations and Wildfire Smoke: A spatio-temporal analysis of an extreme firestorm in San Diego County, California. *Environmental Epidemiology*, 4, doi: 10.1097/EE9.000000000000114.
5. Albano, C. M., Dettinger, M. D., & Harpold, A. A. (2020). Patterns and Drivers of Atmospheric River Precipitation and Hydrologic Impacts across the Western United States, *Journal of Hydrometeorology*, 21(1), 143-159. Retrieved Jul 14, 2021, from <https://journals.ametsoc.org/view/journals/hydr/21/1/jhm-d-19-0119.1.xml>
6. Amini, S., & Straus, D. M. (2018). Control of Storminess over the Pacific and North America by Circulation Regimes. *Climate Dynamics*. doi:10.1007/s00382-018-4409-7
7. Barnston, A.G. and Livezey, R.E. (1987) Classifications, Seasonality, and Persistence of Low-Frequency Atmospheric Circulation Patterns. *Monthly Weather Review*, 115, 1083-1126. [https://doi.org/10.1175/1520-0493\(1987\)115<1083:CSAPOL>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<1083:CSAPOL>2.0.CO;2)
8. Baker, D. and Estes G. (1994). Using the TERC Pattern to Predict Heavy Rainfall in California. *Proceedings of 1994 California Weather Symposium* (<https://cepsym.org/Sympro1994/Baker.pdf>)
9. Bond, N.A., Corin, M.F, Freeland, H. and Mantua N. (2015) : Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophys. Res. Lett*, 42, 3414-3420, doi:10.1002/2015GL063306
10. Chediak, M. and B. K. Sullivan. "Californians Suffer Unprecedented Fire Blackouts in January." *Bloomberg Green*, 16 January, 2021, <https://www.bloomberg.com/news/articles/2021-01-17/parched-california-braces-for-winter-fire-season-blackouts>. Accessed 19 July 2021.
11. Corringham, T.W., F.M. Ralph, A. Gershunov, D.R. Cayan, and C.A. Talbot, 2019b: Atmospheric Rivers drive flood damages in the western United States. *Science Advances*, 5, 12, eaax4631, DOI: 10.1126/sciadv.aax4631
12. DeFlorio, M. J., D.E. Waliser, B. Guan, D.A. Lavers, F.M. Ralph, and F.Vitart, 2018: Global assessment of atmospheric river prediction skill, *Journal of Hydrometeorology*, 19(2), 409-426.
13. Dettinger, M. D., F. M. Ralph, T. Das, P. J. Neiman, and D. R. Cayan, 2011: Atmospheric rivers, floods and the water resources of California. *Water*, **3**, 445–478
14. Dettinger, M. D. (2013). Atmospheric Rivers as Drought Busters on the U.S. West Coast, *Journal of Hydrometeorology*, 14(6), 1721-1732. Retrieved Jul 14, 2021, from https://journals.ametsoc.org/view/journals/hydr/14/6/jhm-d-13-02_1.xml
15. Espinoza, V., D.E. Waliser, B. Guan, D.A. Lavers, and F.M. Ralph, 2018: Global Analysis of Climate Change Projection Effects on Atmospheric Rivers, *Geophys. Res. Lett.*, doi: 10.1029/2017GL076968
16. Estes, G. (1994). Weather Patterns and American River Floods (<https://cepsym.org/Sympro1998/Estes.pdf>)
17. Ferranti, L., L. Magnusson, F. Vitart & D.S. Richardson, 2019: A new product to flag up the risk of cold spells in Europe weeks ahead, *ECMWF Newsletter No. 158*, 15–20.

18. Gershunov, A. and D. Cayan, 2003: Heavy daily precipitation frequency over the contiguous United States: Sources of climatic variability and seasonal predictability. *Journal of Climate*, 16, 2752-2765.
19. Gershunov, A., T. Shulgina, F. M. Ralph, D. Lavers, and J. J. Rutz, 2017: Assessing the climate-scale variability of Atmospheric Rivers affecting the west coast of North America, *Geophys. Res. Lett.* 44, doi:10.1002/2017GRL074175
20. Gershunov, A., T.M. Shulgina, R.E.S. Clemesha, K. Guirguis, D.W. Pierce, M.D. Dettinger, D.A. Lavers, D.R. Cayan, S.D. Polade, J. Kalansky and F.M. Ralph, 2019: Precipitation regime change in Western North America: The role of Atmospheric Rivers. *Sci Rep* **9**, 9944 (2019).
<https://doi.org/10.1038/s41598-019-46169-w>
21. Gershunov, A., J. Guzman Morales, B. Hatchett, R. Aguilera, T. Shulgina, K. Guirguis, J. Abatzoglou, D. Cayan, D. Pierce, P. Williams, I. Small, R. Clemesha, L. Schwarz, T. Benmarhnia, A. Tardy, 2021: Hot and cold flavors of southern California's Santa Ana winds: Their causes, trends, and links with wildfire. *Climate Dynamics*. <https://doi.org/10.1007/s00382-021-05802-z>
22. Gibson, P. B., D. E. Waliser, B. Guan, M. J. DeFlorio, F. M. Ralph, and D. L. Swain (2020), Ridging associated with drought in the Western and Southwestern United States: characteristics, trends, and predictability sources. *J. Climate*, <https://doi.org/10.1175/JCLI-D-19-0439.1>
23. Gibson, P. B., Waliser, D. E., Goodman, A., DeFlorio, M. J., Delle Monache, L., & Molod, A. (2020b). Subseasonal-to-seasonal hindcast skill assessment of ridging events related to drought over the Western United States. *Journal of Geophysical Research: Atmospheres*, 125, e2020JD033655. <https://doi.org/10.1029/2020JD033655>
24. Guan, B., N. P. Molotch, D. E. Waliser, E. J. Fetzer, and P. J. Neiman, 2013: The 2010/2011 snow season in California's Sierra Nevada: Role of atmospheric rivers and modes of large-scale variability, *Water Resour. Res.*, 49, 6731–6743, doi:10.1002/wrcr.20537.
25. Guan, B. and Waliser, D. E., 2015: Detection of atmospheric rivers: Evaluation and application of an algorithm for global studies, *J. Geophys. Res. Atmos.*, 120, 12514– 12535, doi:10.1002/2015JD024257.
26. Guirguis, K., Gershunov, A., Clemesha, R. E. S., Shulgina, T., Subramanian, A. C., & Ralph, F. M. (2018). Circulation drivers of atmospheric rivers at the North American West Coast. *Geophysical Research Letters*, 45, 12–576. <https://doi.org/10.1029/2018GL079249>
27. Guirguis, K., A. Gershunov, T.M. Shulgina, R.E.S. Clemesha, F.M. Ralph, 2019: Atmospheric Rivers impacting Northern California and their modulation by a variable climate. *Climate Dynamics*. <https://doi.org/10.1007/s00382-018-4532-5>
28. Guirguis, K., A. Gershunov, M.J. DeFlorio, T. Shulgina, L. Delle Monache, A.C. Subramanian, T.W. Corringham, and F. M. Ralph, 2020a: Four atmospheric circulation regimes over the North Pacific and their relationship to California precipitation on daily to seasonal timescales. *GRL*. <https://doi.org/10.1029/2020GL087609>.
29. Guirguis, K., Gershunov, A., DeFlorio, M. J., Shulgina, T., Delle Monache, L., Subramanian, A. C., et al. (2020b). Data from: Four atmospheric circulation regimes over the North Pacific and their

- relationship to California precipitation on daily to seasonal timescales. *UC San Diego Library Digital Collections*, <https://doi.org/10.6075/J0154FJJ>
30. Guzman Morales, J., A. Gershunov, J. Theiss, H. Li and D.R. Cayan, 2016: Santa Ana Winds of southern California: Their climatology, extremes, and behavior spanning six and a half decades. *Geophysical Research Letters*, 43, doi:10.1002/2016GL067887.
 31. Guzman Morales, J. and A. Gershunov, 2019: Climate change suppresses Santa Ana Winds of Southern California and sharpens their seasonality. *GRL*, doi: 10.1029/2018GL080261.
 32. Hatchett, B. J., Cao, Q., Dawson, P. B., Ellis, C. J., Hecht, C. W., Kawzenuk, B., et al. (2020). Observations of an extreme atmospheric river storm with a diverse sensor network. *Earth and Space Science*, 7, e2020EA001129. <https://doi.org/10.1029/2020EA001129>
 33. Hecht, C. W., and Cordeira, J. M. (2017), Characterizing the influence of atmospheric river orientation and intensity on precipitation distributions over North Coastal California, *Geophys. Res. Lett.*, 44, 9048– 9058, doi:10.1002/2017GL074179.
 34. Hu H, Dominguez F, Wang Z, Lavers DA, Zhang G, Ralph F (2017) Linking atmospheric river hydrological impacts on the U.S. West coast to rossby wave breaking. *J Clim* 30:3381–3399. <https://doi.org/10.1175/JCLI-D-16-0386.1>
 35. Hughes, M. , & Hall, A. (2010). Local and synoptic mechanisms causing Southern California's Santa Ana winds. *Climate Dynamics*, 34(6), 847–857
 36. Kalnay, E., et al., 1996: The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, 77(3), 437–471.
 37. Kanamaru, H., & Kanamitsu, M. (2007). Fifty-Seven-Year California Reanalysis Downscaling at 10 km (CaRD10). Part II: Comparison with North American Regional Reanalysis, *Journal of Climate*, 20(22), 5572-5592. Retrieved Jun 1, 2021, from <https://journals.ametsoc.org/view/journals/clim/20/22/2007jcli1522.1.xml>
 38. Kolden, C., & Abatzoglou, J., 2018: Spatial distribution of wildfires ignited under katabatic versus non-katabatic winds in Mediterranean Southern California USA. *Fire*, 1(2), 19. <https://doi.org/10.3390/fire1020019>
 39. Krishnakumar, P. and S. Kannan. "The worst fire season ever. Again." *New York Times*, 15 September 2020. <https://www.latimes.com/projects/california-fires-damage-climate-change-analysis>. Accessed 19 July 2021.
 40. Lambrecht, K. M., Hatchett, B. J., Walsh, L. C., Collins, M., & Tolby, Z. (2019). Improving Visual Communication of Weather Forecasts with Rhetoric, *Bulletin of the American Meteorological Society*, 100(4), 557-563. Retrieved Aug 30, 2021, from <https://journals.ametsoc.org/view/journals/bams/100/4/bams-d-18-0186.1.xml>
 41. Lambrecht, K., Hatchett, B. J., VanderMolen, K., and Feldkircher, B.: Identifying community values related to heat: recommendations for forecast and health risk communication, *Geosci. Commun. Discuss.* [preprint], <https://doi.org/10.5194/gc-2021-12>, in review, 2021

42. Livneh, B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K.M. Andreadis, E.P. Maurer, and D.P. Lettenmaier, 2013: A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions. *J. Clim.*, 26, 9384-9392.
43. Mundhenk, B. D., E. A. Barnes, E. D. Maloney, and K. M. Nardi, 2016: Modulation of atmospheric rivers near Alaska and the US West Coast by northeast Pacific height anomalies. *J Geophys Res-Atmos*, 121, 12751-12765.
44. Mundhenk, B. D., Barnes, E. A., Maloney, E. D., & Baggett, C. F. (2018). Skillful empirical subseasonal prediction of landfalling atmospheric river activity using the Madden–Julian oscillation and quasi-biennial oscillation. *Climate and Atmospheric Science*, 1(1), 7. <https://doi.org/10.1038/s41612-017-0008-2>.
45. Murphy, P. (2021, March 19). Preventing Wildfires with Power Outages: The Growing Impacts of California's Public Safety Power Shutoffs. *Physicians, Scientists, and Engineers for Healthy Energy Blog*. <https://www.psehealthyenergy.org/news/blog-posts//>
46. Neiman, P. J., F. M. Ralph, G. A. Wick, J. D. Lundquist, and M. D. Dettinger, 2008: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations, *J. Hydrometeorol.*, 9, 22 – 47.
47. Oakley, N.S., Lancaster, J.T., Kaplan, M.L. *et al.* Synoptic conditions associated with cool season post-fire debris flows in the Transverse Ranges of southern California. *Nat Hazards* **88**, 327–354 (2017). <https://doi.org/10.1007/s11069-017-2867-6>
48. Oakley, N., J. Cannon, F., Munroe, R., Lancaster J., Gombert D., and Ralph F.M., 2018: Brief communication: Meteorological and climatological conditions associated with the 9 January 2018 post-fire debris flows in Montecito and Carpinteria, California, USA. *Nat. Hazards Earth Syst. Sci.*, 18, 3037-3043, <https://doi.org/10.5194/nhess-18-3037-2018>
49. Polade, S. D. and Gershunov, A. and Cayan, D. R. and Dettinger, M. D. and Pierce, D. W., 2017. Precipitation in a warming world: Assessing projected hydro-climate changes in California and other Mediterranean climate regions. *Scientific Reports*. 7. 10.1038/s41598-017-11285-y
50. Porter, Keith A. Overview of the ARkStorm Scenario [electronic Resource] / by Keith Porter ... [et Al.]; Prepared for the U.S. Geological Survey Multihazards Demonstration Project. Reston, Va: Dept. of the Interior, U.S.Geological Survey, 2011. Print.
51. Ralph, F. M., P. J. Neiman, and G. A. Wick (2004), Satellite and CALJET aircraft observations of atmospheric rivers over the eastern North-Pacific Ocean during the El Niño winter of 1997/98, *Mon. Weather Rev.*, 132, 1721–1745
52. Ralph, F. M., P. J. Neiman, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, and A. B. White (2006): Flooding on California's Russian River: Role of atmospheric rivers, *Geophys. Res. Lett.*, 33, L13801, doi:10.1029/ 2006GL026689.
53. Ralph, F. M., P. J. Neiman, G. N. Kiladis, K. Weickman, and D. W. Reynolds (2011), A multiscale observational case study of a Pacific atmospheric river exhibiting tropical-extratropical connections and a mesoscale frontal wave, *Mon. Weather Rev.*, 139, 1169–1189, doi:10.1175/2010MWR3596.1.

54. Ralph, F. M., Rutz, J. J., Cordeira, J. M., Dettinger, M., Anderson, M., Reynolds, D., Schick, L. J., & Smallcomb, C. (2019). A Scale to Characterize the Strength and Impacts of Atmospheric Rivers, *Bulletin of the American Meteorological Society*, 100(2), 269-289. Retrieved Jun 1, 2021, from <https://journals.ametsoc.org/view/journals/bams/100/2/bams-d-18-0023.1.xml>
55. Rhoades, A.M., M.D. Risser, A.S. Dáithí, M.F. Wehner, A.D. Jones, 2021: Implications of warming on western United States landfalling atmospheric rivers and their flood damages, *Weather and Climate Extremes*, Volume 32, 100326, ISSN 2212-0947
56. Rutz, J. J., and W. J. Steenburgh (2012), Quantifying the role of atmospheric rivers in the interior western United States, *Atmos. Sci. Lett.*, 13, 257–261, doi:10.1002/asl.392.
57. Rutz, J. J., W. J. Steenburgh, and F. M. Ralph (2014), Climatological characteristics of atmospheric rivers and their inland penetration over the Western United States, *Mon. Weather Rev.*, 142, 905–921.
58. Rutz, J. J., Steenburgh, W. J., & Ralph, F. M. (2015). The Inland Penetration of Atmospheric Rivers over Western North America: A Lagrangian Analysis, *Monthly Weather Review*, 143(5), 1924-1944. Retrieved Aug 11, 2021, from <https://journals.ametsoc.org/view/journals/mwre/143/5/mwr-d-14-00288.1.xml>
59. Schwarz L., B.J. Malig, J. Guzman Morales, K. Guirguis, A. Gershunov, R. Basu and T. Benmarhnia, 2020: The health burden of fall, winter and spring heat waves in Southern California and contribution of Santa Ana Winds. *Environmental Research Letters*. 15,054017.
60. Siirila-Woodburn, E., Rhoades, Alan M., Hatchett, Benjamin J., Huning, Laurie, Szina, Julia, Tague, C., Nico, Peter S., Feldman, Dan, Jones, Andrew D., Collins, William D., Kaatz, Laura: Evidence of a low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth and Environment*, in press.
61. Sterle, K., Hatchett, B. J., Singletary, L., & Pohl, G. (2019). Hydroclimate Variability in Snow-Fed River Systems: Local Water Managers' Perspectives on Adapting to the New Normal, *Bulletin of the American Meteorological Society*, 100(6), 1031-1048. Retrieved Jul 14, 2021, from <https://journals.ametsoc.org/view/journals/bams/100/6/bams-d-18-0031.1.xml>
62. Straus, D.M., Corti S., Molteni F (2007). Circulation regimes: chaotic variability versus SST-forced predictability. *J Clim.*, 20:2251-2272.
63. Strobino, M.H. and D.W. Reynolds (1995). Forecasting Hydrologically Critical Storms In Northern and Central California. Western Region Technical attachment 95-22, National Weather Service (https://www.weather.gov/media/wrh/online_publications/TAs/ta9522.pdf)
64. Swain, D. L., Tsiang, M., Haugen, M., Singh, D., Charland, A., Rajaratnam, B., and Diffenbaugh, N. S., 2014: The extraordinary California drought of 2013/2014: Character, context, and the role of climate change, *Bull. Amer. Meteorol. Soc.*, 95, S3–S7.
65. Swain, D.L., Langenbrunner, B., Neelin, J.D. *et al.* Increasing precipitation volatility in twenty-first-century California. *Nature Clim Change* **8**, 427–433 (2018). <https://doi.org/10.1038/s41558-018-0140-y>.

66. Swales, D., Alexander, M., and Hughes, M. (2016), Examining moisture pathways and extreme precipitation in the U.S. Intermountain West using self-organizing maps, *Geophys. Res. Lett.*, 43, 1727– 1735, doi:10.1002/2015GL067478.
67. Uccellini, L. W., & Ten Hoeve, J. E. (2019). Evolving the National Weather Service to Build a Weather-Ready Nation: Connecting Observations, Forecasts, and Warnings to Decision-Makers through Impact-Based Decision Support Services, *Bulletin of the American Meteorological Society*, 100(10), 1923-1942. Retrieved Aug 30, 2021, from <https://journals.ametsoc.org/view/journals/bams/100/10/bams-d-18-0159.1.xml>
68. Vahedifard, F., A. Aghakouchak, E. Ragno, S. Shahrokhbabadi, I. Mallakpour, 2017: Lessons from the Oroville dam. *Science*, 17 Mar 2017, 1139-1140.
69. Weaver, R. (1962). Meteorology of hydrologically Critical Storms in California. Hydrometeorological Report No. 37, U.S. Dept. of Commerce, Weather Bureau (now the National Weather Service). (<https://cepsym.org/history/HMR-37.pdf>)
70. Westerling, A. L., D. R. Cayan, T. J. Brown, B. L. Hall, and L. G. Riddle, 2004: Climate, Santa Ana winds and autumn wildfires in southern California. *Eos, Trans. Amer. Geophys. Union*, **85**, 289–296, <https://doi.org/10.1029/2004EO310001>.
71. Wise, E., Wrzesien, M., Dannenberg, M., & McGinnis, D. (2015). Cool-Season Precipitation Patterns Associated with Teleconnection Interactions in the United States. *Journal of Applied Meteorology and Climatology*, 54(2), 494-505.
72. Zhang, Z., Ralph, F. M., & Zheng, M. (2019). The relationship between extratropical cyclone strength and atmospheric river intensity and position. *Geophysical Research Letters*, 46, 1814–1823. <https://doi.org/10.1029/2018GL079071>

Figures

Figure 1

(a) The four North Pacific atmospheric teleconnection patterns (NP4 modes) defined and described in GGR'20 shown here in the phase most associated with wet conditions over California (defined as the positive phase as in GGR'20). The color scale gives the temporal correlation (r) between each teleconnection pattern and the standardized Z500 anomalies at each grid cell (b) locations where more than 50% of Z500 variance is explained by one of the NP4 modes using linear regression with $r^2 > 0.5$, (c) total Z500 variance explained by the joint NP4 modes using multiple linear regression. Figures (a) and (c) are adapted from GGR'20.

Figure 2

Composites of 500 mb geopotential height anomalies for the sixteen recurring winter weather patterns impacting West Coast. The sample size of each weather regime (n) is given in the title as a percentage of total days in the 1949-2017 record. The highlighted +/- in the lower left corner gives the phase of the NP4 modes in the following order: [BP, AP, CP, OC].

Figure 3

Example showing the relationship between the NP4 modes and weather patterns over the North Pacific/western US during WY2017. Daily amplitudes of each mode are shown in (a). These modes can be in- or out-of-phase with each other on a given day, resulting in different phase combinations (b). Three events are identified (E1-E3) when the joint phase combination was the same: The Alaskan-Pacific mode was negative and the other three modes were positive. Composites of Z500 and IVT for these three events are shown in (c) and (d), respectively. The box in (c) shows the region where the NP4 modes are most influential and where the circulation is expected to be largely modulated by the NP4 mode interaction (i.e. the composites should look similar inside the box but not necessarily outside the box)

Figure 4

As in Figure 3 but for WY2021. Three events are identified (E4-E6) when the joint phase combination was the same: The Alaskan-Pacific and Baja-Pacific modes were positive and the Canadian-Pacific and Offshore-California modes were negative.

a) AR landfall probability

b) Precipitation Anomaly

c) Probability of Extreme Precipitation

d) Percent of Total Historical Precipitation

Figure 5

Impacts associated with each weather regime showing (a) AR landfall probability, (b) precipitation anomaly, (c) probability of extreme precipitation, (d) percent of total historical precipitation. Precipitation extremes are daily accumulations above the local 95th percentile. Sample size is important for comparing (c) and (d) where some weather regimes bring high probabilities of extreme precipitation but

are less common and thus do not contribute substantially to the total historical precipitation (e.g. WR7 and WR11, see sample sizes in Figure 2)

Figure 6

Additional impacts associated with each weather regime showing (a) Santa Ana wind probabilities, (b) temperature anomalies, (c) heat wave probability, and (d) extreme cold probability. The temperature plots use daily maximum temperatures. Heat waves (cold extremes) are defined as exceedances above (below) the historical 95th (5th) percentile after removing the seasonal cycle. Filled bars in (a) highlight SAW probabilities above climatology.

Figure 7

The importance of weather regimes 9-12 for California water resources. Panel (a) shows the percent of total historical precipitation that occurred during WR9-12 and panel (b) shows the percent of historical extreme precipitation that occurred during WR9-12. Panel (c) gives the weather regime distribution for the most extreme ARs (scales 4&5) that made landfall along the west coast.

Figure 8

The relationship ($r=0.61$) between snow water equivalent on March 1 at Donner Summit in the Northern Sierra and the frequency of weather regimes 9-12 during November-February.

Figure 9

AR landfalls during select water years when historical floods occurred, where the y-axis gives the coastal latitude and the x-axis gives the date in the season. The maker size shows the magnitude of AR IVT (daily average) and the color scale gives the weather regime observed for each day. Eight flood events (F1-F8) are highlighted for further discussion.

Figure 10

Observed Z500 anomalies for the day with the most intense AR footprint over California for each flood event, defined by the summed IVT over California. The weather regime classification for each day is given as highlighted text in the lower left corner of each map.

Figure 11

Observed IVT for the same days shown in Figure 10.

Figure 12

The weather regime distribution of Southern California wildfire starts.

Figure 13

As in Figure 9 but for the 2017-2018 season and showing the timing and latitude of the Thomas Fire (a). The weather regime distribution from the ignition date to full containment (December 4-January 12) is shown in (b).

Figure 14

Observed frequency of each weather regime during Nov-Feb (black) and statistically significant ($p < 0.05$) trends colored red for increasing trends or blue for decreasing trends.

Figure 15

The combined seasonal frequency of WR11, WR12, and WR14 with the long-term trend (a), and the combined seasonal frequency and trend of WR1, WR4, and WR5 (b). Both trends are statistically significant ($p < 0.001$).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterial.pdf](#)