Atmospheric River Families: Definition and Associated Synoptic Conditions

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ABSTRACT

Atmospheric rivers (ARs) can cause flooding when they are strong and stall over an already wet watershed. While earlier studies emphasized the role of individual, long-duration ARs in triggering floods, it is not uncommon for floods to be associated with a series of ARs that strike in close succession. This study uses measurements from an atmospheric river observatory at Bodega Bay (BBY), in Northern California, to identify periods when multiple AR events occurred in rapid succession. Here, an AR “event” is the period when AR conditions are present continuously at BBY. An objective method is developed to identify such periods, and the concept of “AR families” is introduced. During the period studied there were 228 AR events. Using the AR family identification method, a range of aggregation periods (the length of time allowed for ARs to be considered part of a family) was tested. For example, for an aggregation period of 5 days, there were 109 AR families, with an average of 2.7 ARs per family. Over a range of possible aggregation periods, typically there were 2–6 ARs per family. Compared to single AR events, the synoptic environment of AR families is characterized by lower geopotential heights throughout the midlatitude North Pacific, an enhanced subtropical high, and a stronger zonal North Pacific jet. Analysis of water year 2017 demonstrated a persistent geopotential height dipole throughout the North Pacific and a positive anomaly of integrated water vapor extending toward California. AR families were favored when synoptic features were semistationary.

1. Introduction

An atmospheric river (AR) is defined as a long, narrow, and transient corridor of strong horizontal water vapor transport typically associated with an extratropical cyclone (Zhu and Newell 1998; Ralph et al. 2004, 2005; Guan and Waliser 2017; Ralph et al. 2017). ARs are the primary mechanism for water vapor transport into the midlatitudes although they cover 10% or less of the globe (Zhu and Newell 1998). ARs are characterized by abundant moisture in the lower troposphere and the presence of a low-level jet, and they can contribute to extreme precipitation (Dettinger et al. 2011; Lamjiri et al. 2017). Globally, ARs most frequently impact the windward side of continents (Guan and Waliser 2017), though ARs have supported extreme precipitation in other locations too, such as the eastern or central United States (Moore et al. 2012; Lavers and Villarini 2013; Mahoney et al. 2016). Through mechanisms such as lifting associated with fronts and orographic lift upon interaction with terrain, ARs can produce heavy rain (Ralph et al. 2011, 2013; Rutz et al. 2014; Lamjiri et al. 2017) and flooding (Ralph et al. 2006; Neiman et al. 2008, 2011; Ralph et al. 2013).

While the entire U.S. West Coast is impacted by ARs, Northern California’s Russian River watershed in particular receives 60%–70% of its total annual precipitation from ARs (Gershunov et al. 2017), and ARs were associated with all seven floods that occurred in the watershed between 1997 and 2006 (Ralph et al. 2006). Between the two ingredients necessary for high precipitation, rainfall rate and duration (Doswell et al. 1996), within California, storm duration is a strong indicator for higher precipitation and streamflow totals (Ralph et al. 2013; Lamjiri et al. 2017); orientation and water vapor transport intensity have also been shown to impact precipitation distributions from ARs in the Russian River watershed (Hecht and Cordeira 2017). Ensemble forecasts (from 1- to 16-day lead times) of western United States landfalling ARs, in terms of the integrated water vapor transport, exhibit higher skill than ensemble forecasts of precipitation distributions at the same spatial scale (Lavers et al. 2016), and this can

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improve situational awareness. However, the intensity and duration of ARs are difficult to accurately forecast at the temporal and spatial resolution necessary to provide information critical for water management decisions and emergency preparedness (Ralph et al. 2019a). AR forecast skill degrades with increasing lead time and exhibits significant errors in landfall location, up to 800 km over a 10-day lead time (Wick et al. 2013; Nardi et al. 2018). While AR forecasts do improve within a 4-day lead time as ARs approach the coast, there are still inaccuracies in AR amplitude, position, and duration that can lead to impactful forecast errors in precipitation distribution both in coastal and inland regions (Ralph et al. 2011).

While ARs are synoptic-scale features that can span entire ocean basins, smaller-scale features can not only influence forecast skill but also alter hydrologic impacts. Mesoscale frontal waves (MFWs) associated with an AR can modify the spatial distribution of the AR and increase the total event precipitation (Ralph et al. 2011). For one case in Southern California, an AR affected by a MFW caused an increase in the convergence and ascent along frontal boundaries within the AR, accounting for 35%–36% of the storm total precipitation, 3 times larger in the region influenced by the MFW (Neiman et al. 2004). Persistent ARs with durations longer than 63 h (the 85th percentile) have a much greater moisture content than nonpersistent ARs, enhancing the hydrologic impact of these events (Payne and Magnusdottir 2016). This aligns with observations of higher precipitation accumulations and streamflow impacts from longer duration storms (Ralph et al. 2013; Lamjiri et al. 2017). Dynamical mechanisms, such as Rossby wave breaking and North Pacific jet dynamics, which act on longer temporal and spatial scales than AR events, foster AR and cyclone development (Hu et al. 2017; Mundhenk et al. 2016; Griffin and Martin 2017) and can modulate AR duration as well.

Water year (WY) 2017 (1 October 2016–30 September 2017) was a record wet year in Northern California. Many ARs were observed to be more impactful simply by virtue of arriving shortly after a previous AR, where the watershed had yet to recover its storage space in streams and soils to accommodate additional rainfall. This led to additional flooding. These ARs were not necessarily long duration ARs or persistent ARs, but rather a series occurring in close temporal proximity. To explore the dynamical forcings and synoptic regimes through this lens to gain greater insight into the relevant scales, mechanisms, and potential predictability of these phenomena, we introduce the term “AR families,” which will be defined in detail in section 2. While assessing the direct impacts of AR families is out of the scope of this study, case study analyses of AR families compared to single AR events show increased precipitation totals and elevated stream discharge rates for AR families (not shown).

While ARs have not previously been classified in precisely this way, cyclone families were first identified in the literature by Bjerknes and Solberg (1922) and have been shown to produce greater impacts than individual cyclones (Vitolo et al. 2009). Cyclone families exhibit periodicity, enabling the division of cyclones into groups. Families develop along the same polar front with the first cyclone traveling along a track north of the family and the last cyclone so far south it reaches the trade winds. As a cyclone family passes a fixed point, usually four cyclones can be observed, although that number can vary considerably from one family to another (Bjerknes and Solberg 1922). Extratropical cyclones (ECs) frequently occur all over the globe independent of ARs; however, 82% of ARs are associated with ECs in the North Pacific (Zhang et al. 2019). Therefore, we will begin our assessment of AR families by reviewing the methodologies used to investigate cyclone families.

Mailier et al. (2006) investigated cyclone families in western Europe, and noted that the complexity and variety of mechanisms that govern fronts and cyclones may generally indicate that cyclone clusters can be produced by a wide variety of synoptic regimes and multiscale processes. Methods including serial randomness, clustering, and regularity for identification of cyclone families were also described therein. Pinto et al. (2014) further found that, in the same region, the serial clustering of cyclones occurs more frequently than expected by chance, suggesting dynamical mechanisms may favor their occurrence. Numerical simulations of general atmospheric circulation led to the conclusion that parent cyclones, through the production of fronts, can create smaller, at times multiple, secondary cyclones (Eliassen 1966). Multiple cyclones in Norway throughout December 2006 combined with the meridional transport of moisture through associated ARs led to above average temperature and precipitation during that month (Sodemann and Stohl 2013). In the North Pacific storm track, downstream energy dispersion from baroclinic waves extending eddy activity eastward toward areas of less baroclinicity can play a role in the initiation of cyclone families (Chang and Orlanski 1993, 1994). Upstream development has also been attributed to the genesis of cyclone families (Wernli et al. 1999).

In this work, we will use a combination of in situ observations and reanalysis to first create a catalog of AR families, where our identification methodology is informed by the literature on cyclone families and
long-duration, persistent ARs, and then conduct a thorough evaluation of the synoptic environment in which they occur. Our hypothesis is that if the large-scale environment conducive to the continuous production and evolution of ARs to form an AR family is identifiable, then perhaps these impactful periods can be predicted with better skill than for individual ARs.

This study is organized as follows. In section 2, a description of the algorithm created to identify AR families, including the observational data used to determine the presence of an AR, is presented, along with the method used to calculate anomalous and climatological values of large scale atmospheric conditions from reanalysis. Section 3 provides statistics related to the occurrence of AR families and describes their synoptic-scale characteristics in the Russian River watershed. Section 4 continues this synoptic evaluation of AR families and includes a discussion of the synoptic-scale differences between all AR families, single AR events, AR families with multiple AR events and AR families with few AR events. Section 5 provides a case study of WY 2017. Section 6 includes the conclusion and discussion.

2. Methods

a. Observational data

As part of the California Department of Water Resources Enhanced Flood Response and Emergency Preparedness Program, networks of observing stations have been established to monitor and study ARs along the U.S. West Coast (White et al. 2013). This includes stations known as atmospheric river observatories (AROs), which are at a minimum equipped with vertically profiling wind radars, global positioning system (GPS) receivers, and surface meteorology sensors including temperature, relative humidity, precipitation, and pressure.

This study uses the Ralph et al. (2013) methodology to create a catalog of AR events based on AR conditions observed at the Bodega Bay (BBY) ARO in the Russian River watershed (38°N, 123°W) from 13 November 2004 through 31 April 2017. These start and end dates encompass all months and days between them, and were chosen based on the start of available data (see Ralph et al. 2013), and the last full month of available data at the time that this study began. AR events were identified via three criteria: integrated water vapor (IWV) equal to or exceeding 2 cm, upslope IWV flux perpendicular (230°) to the local mountains equal to or exceeding 15 cm (m s⁻¹) and both variables continuously meeting or exceeding these conditions for a minimum of 8 h. These criteria were determined to be optimal constraints on Northern California ARs through the evaluation of AR precipitation over almost ten winter seasons by Neiman et al. (2009) and Ralph et al. (2004, 2006). Based on results from Neiman et al. (2009) areas of orographic enhanced precipitation can be identified by determining the position of the controlling layer, which is defined as the layer of maximum correlation between the horizontal component of the upslope wind and the rainfall downwind in the mountains. In Northern California, the controlling layer is at roughly 1 km above sea level, which makes physical sense given that the water vapor is primarily located in the lowest few kilometers along the coastal region. The upslope IWV flux can then be computed by combining the upslope winds of a vertically pointing wind profiler, and the GPS derived IWV to identify AR conditions at BBY (Ralph et al. 2006). In total, 228 AR events were identified year-round beginning in November 2004 and ending in April 2017.

Due to various factors, most importantly mechanical outages, periods of data are missing from this observational dataset. Ralph et al. (2019b) maximized the amount of data available by compiling data from the ARO IWV flux table data output, raw observations from the profiler and GPS sensors, and the AR catalog in Ralph et al. (2013), in that order. However, that still left over 36 000 h of missing data over the entire period of record, which results in an undercounting of overall AR events. In WY 2013 alone, 77% of October–March hourly data records are missing. The ARO reported observations of five ARs during WY 2013, which is about one-quarter of the average yearly AR count at this location. Using this observational dataset, the average number of AR events per year, excluding WY 2013, is 19.

Despite the periods of missing data, this observational dataset was chosen to identify AR events and AR families due to its unique hourly resolution for AR event onset and cessation. The accuracy in duration of AR events was important for correctly identifying AR families.

This study, like Ralph et al. (2013), uses AR conditions at a point to identify AR events. This is distinct from other AR identification algorithms that identify AR objects in reanalysis datasets. Ralph et al. (2019b) assesses the difference between these types of algorithms at BBY and found that while the observational based AR catalog may underestimate the number of AR events it otherwise agrees well with reanalysis based AR catalogs. The updated AR catalog was compared against the Rutz et al. (2014) AR catalog which defines AR objects based on a continuous region ≥ 2000 km in length and integrated water vapor transport ≥ 250 kg m⁻¹ s⁻¹ to confirm identification of AR events through this
methodology. Despite the large periods of missing data from the updated Ralph et al. (2013) AR catalog, there was general agreement in both catalogs to observe the same AR events (not shown).

b. Reanalysis data

The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), dataset (Gelaro et al. 2017) was used to create a daily climatology of several relevant atmospheric variables. The MERRA-2 dataset was used due to its high spatial resolution, 0.625° × 0.5° (longitude–latitude), improved representation of extreme precipitation events, and length of analysis period. MERRA-2 assimilates a high volume of meteorological data, including space-based estimates of aerosols, GPS radio occultation measurements, and ozone profile observations. MERRA-2 also assimilates observations from numerous satellites that observe atmospheric motion and surface wind vectors influential for U.S. West Coast phenomena, such as ARs.

The daily climatology was created using a 30-yr (1987–2016), 21-day running mean technique (Hart and Grumm 2001) of the following relevant atmospheric variables: 500- and 850-hPa geopotential heights, 850-hPa air temperature, 250-hPa wind speed, and IWV. A climatology and composite analysis of integrated water vapor transport, often an important identifier of AR activity, was not shown for this study. This analysis would be important to address potential intensity differences between the climatological background, AR events and AR families, which are relatively small (on the order of 20 kg m⁻¹ s⁻¹) at landfall in the composites. A detailed investigation of AR intensity is out of the scope of this paper. This climatology was used to create a background seasonal climatology for December–February (DJF) to calculate anomalous characteristics of AR events and AR families. While the AR events and families can occur during any time of the year, we focus the background climatology on DJF because it has the highest climatological frequency of AR occurrence (Gershunov et al. 2017; Lamjiri et al. 2017).

These reanalysis data were sampled to create mean and anomaly composites of different subsets of identified AR families (e.g., number of distinct ARs in a family; length of aggregation period). The composites are calculated throughout the duration of the AR family. Using these composites, the difference between the population means was calculated. The Welch’s t test determined whether the differences were statistically significant at the 99% confidence level. The Welch’s t test is ideal for this application as it is designed for different sample sizes, and allows for the calculation of the degrees of freedom for individual grid boxes.

c. AR families algorithm

AR families are two or more distinct AR events that occur within a given aggregation period. During development of this algorithm, we explored how different aggregation periods change the distribution of AR families. Aggregation periods, calculated from the end time of the first AR, were binned using 12- and 24-h time intervals, with the overall periods considered ranging from 12 to 216 h. The shortest aggregation period used was determined by the distribution of time between all AR events within the AR catalog from 0 to 600 h; the maximum number of AR events occur within 12 h of one another (Fig. 1). The longest aggregation period was based on cyclone family literature, which categorized the persistence of the atmosphere and cyclone clustering to occur between 6 and 9 days (144–216 h) (Nakamura 1992; Nakamura and Sampre 2002; Pinto et al. 2014).

Identifying a suitable maximum aggregation period for AR families impacting Northern California is one
fundamental contribution of this study. Mailier et al. (2006) discussed the idea of serial regularity, where there is a natural cause for regular patterns such that there is a minimum permissible distance and time between any two events. ECs in particular have associated spatial scales in which successive cyclone centers cannot be closer than the combined radii of the cyclones, leading to the expectation of a regular pattern especially during instances of high cyclone rates. In this study, maximum aggregation periods between 120 and 600 h were evaluated. The leveling off in the increase in additional AR families after the 120-h aggregation period led to the decision to evaluate the synoptic regimes of AR families at the 120-h aggregation period (Fig. 1). While the extended analysis out to 600 h shows there are multiple scales at which AR families impact Northern California, with secondary increases in AR families from 144 to 240 h and a third increase from 360 to 480 h, this 120-h threshold will allow a focus on AR families that occur within a subweekly period that could be associated with baroclinic waves or migratory eddies (Nakamura 1992; Nakamura and Sampre 2002).

Using the updated ARO catalog, the time between the end of the first AR event and the start of the second AR event was calculated. The count of AR events within an AR family continues until the time between the end of the first event and the start of subsequent AR events is greater than the longest aggregation period. AR families can become enhanced, with a higher count of AR events in the family, when the aggregation period increases (e.g., if there are two ARs in a 72-h aggregation period, and another one or more is added when the aggregation period increases to the 120-h aggregation period) (Fig. 2). Due to the 12-h separation in aggregation periods and the minimum duration required for an AR, any AR family that has more than two AR events is considered an enhanced AR family. Each AR event is counted once per aggregation period for a distinct count of the total number of AR events in each AR family for the associated aggregation period. As the aggregation period lengthens, the chance of another AR event occurring increases. The increase in aggregation period length could therefore allow two AR events categorized as single ARs to constitute an AR family in a longer aggregation period. Consider two ARs, where the second AR starts 78 h after the end of the first AR. In a 72-h aggregation period, these would be considered two single AR events. However, in a 120-h aggregation period, these two events would be an AR family. Therefore, lengthening the aggregation period can increase the number of AR families initiated.

A summary of terms used throughout the study are as follows:

- **AR event**: AR conditions observed at the BBY ARO for at least 8 continuous hours.
- **AR family**: two or more AR events occurring within one aggregation period.
- **Enhanced AR family**: an AR family that is composed of subsets of at least one other AR family identified within shorter aggregation periods.
- **Aggregation period**: the length of time, in hours, allowed between the end of the first AR event and the start of serial AR events. All AR events within the aggregation period are counted as one AR family.
- **Total family duration**: the number of hours from the start hour of the first AR event in the AR family to the end hour of the last AR event within the AR family.

We hypothesize that AR families can originate from multiple dynamic regimes. To stratify AR families into
subsets, we completed subjective visual comparison of case studies, looking primarily at different aggregation period lengths and different numbers of AR events within families. The visual inspection of various case studies allowed us to identify patterns within subsets that when viewed as a whole contain large variability. Two distinct subsets of AR families arose and were then selected for further analysis to compare their synoptic environments and investigate our hypothesis. The first subset is composed of AR families consisting of two AR events separated by 12 h or less, which could be associated with a mesoscale frontal wave. The second subset is composed of AR families consisting of 3+ AR events within the 120-h aggregation period, which could be associated with a large parent cyclone with multiple short wave propagations. Thus, the following terms are introduced (Fig. 2):

1) Dual-AR event AR family: a two AR event family within the 12-h aggregation period.
2) Multi-AR event AR family: a three or more AR event family within the 120-h aggregation period.

During the period from November 2004 through April 2017, the BBY ARO catalog reports 228 AR events. The AR family algorithm shows that 109 of those events (47.8% of the total) occur within 120 h of one another. In the next section, MERRA-2 reanalysis is used to investigate characteristics of AR families identified within the BBY ARO catalog, which will hereafter be referred to as the AR families catalog.

3. Characteristics of atmospheric river families

We used the AR families catalog to investigate and quantify general characteristics of AR families such as frequency, seasonality and interannual variability. To pick the most suitable maximum aggregation period for AR families in Northern California, the distribution of AR families across a range of aggregation periods was evaluated and this is described in section 2. This evaluation also included an assessment of the effect of maximum aggregation period on AR characteristics of interest. As mentioned in section 2, maximum aggregation periods of 120–216 h were evaluated based on previous cyclone family literature. The 216-h aggregation period results are presented in this section to assess the upper bound of the maximum aggregation period.

While the number of new AR families increases with aggregation period (Fig. 3a), the longer aggregation periods do not initiate as many new AR families. Instead, the longer aggregation periods generally lengthen preexisting AR families and increase the number of AR events per AR family (enhanced AR families, Fig. 3b). Specifically, the number of new AR families increases by >10 out to the 60-h aggregation period, then increases more gradually out to 216 h (Fig. 3a).

The number of AR families that have exactly two AR events is largest at the 72-h aggregation period (Fig. 3b). The increase in the number of AR events per AR family as aggregation period lengthens is well depicted in the average number of AR events per AR family, which
increases from 2.0 to 3.2, at the 12- and 216-h aggregation period, respectively (Fig. 3b). Throughout all aggregation periods, the number of AR events per AR family ranges from two to six AR events. The distribution changes according to the aggregation period used with Multi-AR Event AR families occurring in the longer aggregation periods (Fig. 3b). For example, within the 216-h aggregation period, there are 66 two-AR event families, 43 three-AR event families, 19 four-AR event families, 10 five-AR event families, and 1 six-AR event family (Fig. 3).

There is large variance in the total number of AR events and AR families between water years (Fig. 4b). WY 2017 contained the largest observed number of AR families, totaling 26 families using the 216-h aggregation period. There were 34 AR events during WY 2017, and only 8 AR events were not considered part of an AR family. WY 2013 recorded one five-AR event family, and no single AR events, but is misrepresented here due to the large periods of missing data previously mentioned in section 2. There is WY to WY variance between the total number of AR families; however, there is also variance within each WY dependent on the aggregation period (Fig. 4b). For some years, WY 2010 or 2012 for example, extending the aggregation period does not make a large difference. For these WYs, AR families occur far enough apart that extending the aggregation period does not increase the number of AR families. Comparatively, in WYs 2006 and 2015, the number of AR families greatly increases with aggregation period.

Seasonality also plays a role in the frequency of AR families. AR families, like AR events in general in this region, occur more frequently between December and February, with 70 families (50.36% of all AR families) occurring during these months for the 216-h aggregation period (Fig. 4a). Two secondary maxima occur during March–May (MAM) and September–November (SON), with 29 and 34 AR families (20.86% and 24.46% of all AR families), respectively, observed (Fig. 4a).

After meeting the temporal criterion at the BBY ARO, AR families are assessed based on their composite spatial structure. AR families exhibit a zonal 250-hPa jet stream with two embedded jet streaks, one in the eastern and western Pacific, respectively (Fig. 5a). Zonally oriented geopotential heights at 500 hPa can also be found across the Pacific but curve cyclonically as they approach the U.S. West Coast (Fig. 5a). The 850-hPa geopotential heights indicate a region of lower geopotential heights near the Alaska coastline but are otherwise zonal in nature (Fig. 5b). The IWV composite highlights the enhanced water vapor content extending from the tropics and impacting the U.S. West Coast (Fig. 5b).

AR families are also assessed on their synoptic differences from the 30-yr MERRA-2 DJF climatology described in section 2. On average, AR families show statistically significant (not shown) anomalous patterns from the DJF climatology (Fig. 6). Composites of all AR families, throughout the total family duration, have an anomalously low geopotential height center off the coast.
of British Columbia at 500 and 850 hPa (Figs. 6a,c). These 109 AR families also have a cyclonically curved, enhanced jet at 250 hPa with the positive wind speed anomalies located above BBY, suggesting a zonal extension of the North Pacific jet stream (Fig. 6b). The location of the jet exit region with respect to BBY and enhancement for AR families is important for understanding the associated circulation pattern of rising (sinking) motion on the cyclonic or cold (anticyclonic or warm) side of the jet (Namias and Clapp 1949; Murray and Daniels 1953; Uccellini and Johnson 1979; Uccellini and Kocin 1987), helping to identify areas of storm development or suppression. The anomalous IWV observed in AR families is in a southwest to northeast orientation from 140°W to inland California highlighting a common AR configuration, often termed the Pineapple Express (as described in Dettinger et al. 2011) (Fig. 6d). This result is consistent with findings from Payne and Magnusdottir (2016), which identified larger moisture content for persistent AR events compared to nonpersistent ARs.

4. Synoptic-scale patterns associated with atmospheric river family subsets

To investigate the hypothesis that AR families are associated with different synoptic regimes than single
AR events a synoptic scale evaluation of AR families and single AR events was completed. The difference between average population subsets was computed to evaluate how the synoptic-scale conditions in AR families differ from single AR events and within subsets of AR families.

The composite of single AR events exhibits a zonal 250-hPa jet stream from Japan to 180° (Fig. 5c). Closer to the U.S. West Coast, cyclonically curved wind speeds increase 4–8 m s$^{-1}$ compared to the western Pacific (Fig. 5c). A discontinuous region of greater than 36 m s$^{-1}$ wind speeds is collocated with a weaker 500-hPa geopotential height gradient between 180° and 150°W (Fig. 5c). The composite of 850-hPa geopotential heights highlights the change in geopotential height gradient in the western Pacific compared to the eastern Pacific (Fig. 5d). The IWV composite of single AR events features enhanced water vapor poleward from Hawaii to California and between 150°E and 180° (Fig. 5d).

a. AR families compared to single AR events

AR families (109 AR events) in comparison to single AR events (119 AR events) have a zonally extended area of lower geopotential heights across the North Pacific, seen in both the middle (500 hPa) and lower (850 hPa) atmosphere (Figs. 7a,c). The zonally elongated geopotential height differences could be a reflection of the occurrence of multiple successive ECs, favoring AR families, opposed to single AR events. This result is also suggestive of the presence of a North Pacific waveguide associated with the development of successive ECs and accompanying ARs, which led to these successive AR events. AR families show significant higher subtropical geopotential heights with the leading edge of this region reaching up to 35°N (Figs. 7a,c). The location and amplitude of this anticyclone can displace the landfalling location of AR events through the interaction of these opposite sign anomalies (Wallace et al. 1988). Analysis of the 250-hPa wind speed difference shows a significantly enhanced jet streak for AR families relative to single AR events (Fig. 7b). The jet streak, centered around 40°N and 150°W, is embedded within a stronger zonal jet stream that extends to the U.S. West Coast compared to single AR events (Fig. 7b). A stronger and more zonally extensive jet stream across the North Pacific in the AR family composite suggests an enhanced waveguide for the propagation of successive baroclinic waves toward the U.S. West Coast, favoring the occurrence of AR families. The IWV difference between AR families and single AR events emphasizes regions where single AR events had higher moisture content (Fig. 7d). The difference between these two subsets

FIG. 7. Composites of the difference between 120-h AR families and all single AR events at BBY. Significance at 99% confidence is marked by hatching. Shown are (a) 500-hPa geopotential heights (m), (b) 250-hPa wind speed (m s$^{-1}$), (c) 850-hPa geopotential heights (m), (d) IWV (mm), and (e) 850-hPa temperature (K).
shows significantly more moisture around Hawaii and in the North Pacific for single AR events, suggesting that single AR events have more meridional variability. AR families do exhibit significant positive IWV differences in the central/southern Central Valley in California. Although not directly relatable to inland IWV for the southern Central Valley, the San Francisco Bay Area terrain gap is a well-defined corridor for vapor transport into the northern Central Valley (Lamjiri et al. 2018), alluding to the potential influence of terrain in this region as well. While not significant, differences are also seen in the northern Central Valley. The difference between AR families and single AR events show warmer tropical regions and cooler midlatitude regions for AR families, suggesting enhanced baroclinicity favoring development and rapid eastward movement of ECs and ARs (Fig. 7e).

AR families, when compared to single AR events, indicate significant lower geopotential heights throughout the North Pacific, higher subtropical geopotential heights, a stronger zonally extended jet stream, higher IWV content close to the California coast and warmer tropical air temperature. Single AR events show significantly higher wind speeds, moisture content and air temperature along the Aleutian Islands, AK. These results lead to the prospective hypothesis that single AR events travel meridionally more than AR families, and that zonally traveling ARs may be more likely to be part of families through the zonally oriented baroclinic zone across the Pacific Ocean that previously has been shown to favor the repeated development of cyclones (Bjerknes and Solberg 1922).

b. Multi-AR event AR families versus dual-AR event AR families

From a hydrometeorological perspective, the longer lasting an AR event, the greater the potential for a high precipitation event, saturated soils, and higher streamflow (Ralph et al. 2013; Lamjiri et al. 2017). Therefore, given the right preconditioning provided by the first event(s) in an AR family, there is a potential increased risk of hazardous impacts. To investigate whether longer lasting AR families are associated with different synoptic-scale circulations than shorter duration AR families, the 120-h families were broken into two groups and analyzed as in section 4a: multi-AR event AR families, greater than three AR events per AR family via the 120-h aggregation period, and dual-AR event AR families, two AR events per AR family via the 12-h aggregation period (see section 2).

Composite analysis of multi-AR event AR families indicates a trans-Pacific zonally oriented, strong 250-hPa jet stream (Fig. 8a). Wind speeds are greater than 44 m s⁻¹ across the entire Pacific Ocean (Fig. 8a). There is a wide, greater than 24-mm swath of IWV extending from the tropics to the U.S. West Coast and a broad plume of IWV extending from 120°E to 180°, up to 30°N (Fig. 8b).

Dual-AR event AR families are associated with a ridge over the central North Pacific and a trough over the eastern North Pacific at 500 hPa (Fig. 8c). The 250-hPa wind speeds are strong, greater than 40 m s⁻¹,
across the Pacific basin but are discontinuous in the fastest wind speeds, potentially due to a relatively weak geopotential gradient from the ridge (Fig. 8c). There could also be a smoothing effect here from the composite. IWV is above 20 mm, the minimum AR threshold, but not consistently greater than 24 mm between the tropics and subtropics (Fig. 8d). This composite also highlights 850-hPa geopotential heights below 1300 m off the coast of British Columbia, Canada, which are lower than the minimum geopotential heights for the multi-AR event AR families in the eastern Pacific (Fig. 8d).

Comparing these two subsets of AR families, the dominant feature of the geopotential height fields is the negative geopotential height differences for multi-AR event AR families over the central Pacific basin (Figs. 9a,c). At both 500 and 850 hPa, the lower geopotential heights exhibit a large meridional extent for multi-AR event AR families compared to dual-AR event AR families (Figs. 9a,c). At 850 hPa the negative geopotential height differences extends well into the tropics, below 20°N (Fig. 9c). The negative geopotential height differences at 500 hPa between the multi-AR event AR families and dual-AR event AR families are consistent with positive differences in the 250-hPa wind speed extending across the North Pacific. Dual-AR event AR families have significantly higher 250-hPa wind speed around the Aleutian Islands, similar to what was discovered when comparing AR families and single AR events (Fig. 9b). Multi-AR event AR families are associated with higher IWV values in tropical and subtropical moisture regions (south of 30°N) while dual-AR event AR families are associated with midlatitude (30°–45°N) higher IWV values (Fig. 9d). The multiple areas of positive IWV difference extending from the tropics into the subtropics, highlighted for multi-AR event AR families, overlaps with the negative geopotential height differences in the central Pacific (Figs. 9a,c,d). Evaluating the 850-hPa temperature differences between these two AR family subsets shows warmer temperatures for dual-AR event AR families from 25° to 30°N and extending from 160° to 140°W (Fig. 9e). The AR families with more AR events instead have warmer temperatures around Hawaii and the Aleutian Islands. The co-occurrence of warmer temperatures and higher moisture content around Hawaii is suggestive of Pineapple Express–type AR events (Figs. 7d,e).

Multi-AR event AR families exhibit a region of lower geopotential heights extending farther into the central Pacific, a stronger jet stream from 25° to 40°N, warmer tropical temperatures, and higher moisture content in
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the subtropics and tropics than the dual-AR event AR families. Compared to multi-AR event AR families, dual-AR event AR families display a stronger jet north of 40°N, a zonally extended region of higher moisture, and warmer temperatures in the midlatitudes. These conclusions could imply different processes acting to establish the regimes of multi- versus dual-AR event AR families, such as a large negative geopotential height region in the middle of the North Pacific basin embedded with multiple shortwave disturbances, which could produce independent ECs, or mesoscale frontal waves affecting landfalling AR events. Documenting these robust signals in the average synoptic state for each subset may help to enhance situational awareness of these events. Future work may assess the potential increase in lead times for the predictability of the associated synoptic regimes leading to AR families. These synoptic regimes can also be applied to seasonal-to-subseasonal predictions to note their frequency in extended range forecast products and link their occurrence to precipitation anomalies on the U.S. West Coast.

5. Water year 2017 case study

WY 2017 was record breaking in many regards: there were 34 AR events to hit the Russian River watershed; the North Sierra precipitation 8-station index, provided since 1922 by the California Department of Water Resources (cdec.water.gov), received record precipitation with a total of 94.7 in. (2405.38 mm), and Oroville Dam in Butte County, California, suffered significant damage to its main and emergency spillways prompting the evacuation of over 188,000 people (White et al. 2019). These conditions were preceded by AR events occurring in series, that is, AR families, significantly impacting water resource management and the public.

As previously discussed, AR duration has been identified as the leading driver in precipitation totals (Lamjiri et al. 2017) and doubling AR duration produces 6 times the streamflow potential (Ralph et al. 2013). AR families last an average of 86 h from the start of the first AR event to the end of the last AR event (total family duration), with AR conditions present, on average, during 40 of these hours. A 40-h series of ARs is double the average duration of a single AR event (Ralph et al. 2013). AR families thus pose potentially higher risks from excessive precipitation, soil moisture, and streamflow than single AR events, making WY 2017s numerous AR families even more impactful than other WYs. WY 2017 saw a total of 12 two-AR families, 6 three-AR families, 3 four-AR families, 1 five-AR family, and 1 six-AR family determined via the 120-h aggregation period (Table 1).
To investigate AR events as well as break periods throughout the family, we calculated the ratio of total AR hours to total family duration for all AR families (Fig. 10). If single AR events were included they would fall on the one-to-one line as their ratio of AR hours to total family duration is equal. Dual-AR event AR families are close to the one-to-one line with a range of total family durations (Fig. 10a). Multi-AR event AR families have a higher ratio of AR hours to total family duration, which could be due to the higher number of AR events per AR family. Many WY 2017 AR families were long in duration with a higher ratio of AR hours to total family duration (Fig. 10b). Throughout the aggregation periods, the average number of AR hours is 40. However, as total family duration exceeds 100 h the number of AR hours within the AR family increases to an average of 54.4 h (Fig. 10).

The difference between the composite of the WY 2017 AR families from that of all AR families highlights the variation in synoptic conditions during WY 2017. The two significant and persistent high geopotential height regions at 500 and 850 hPa outline the favored corridor for storm tracks into the Northern California area (Figs. 11a,c). An alternating pattern of high and low geopotential height regions as seen in Fig. 11 is suggestive of a potential Rossby wave train mechanism. The low geopotential height areas are elongated zones stretching from Hawaii to California instead of large circular areas seen in other composites. This is similar to results from previous studies evaluating Rossby wave propagation (Hsu and Lin 1992), however a full hemispheric analysis has not been completed in this study (Figs. 11a,c). The 250-hPa positive wind differences are positioned farther south, around Hawaii, approximately 25°N, instead of 35°–40°N, as found in previous locations for this study, aligning with the lower geopotential height region off the California coast (Fig. 11b). The wind speed is significantly stronger during WY 2017 AR families than in the composite of all AR families. A likely important contributor to the anomalous nature of this WY was the immense amount of water vapor available for transport. The location, positioned in the anomalously warm sector, and the amount, more than 8 mm higher than all AR families, of the moisture availability likely contributed to exceptionally wet conditions in Northern California (Fig. 11d). Air temperature at 850 hPa reflects the consistently warmer conditions in the tropics, south of 25°N to west of 130°W and south of 30°N, extending to coastal Mexico, for WY 2017 AR families, which is even warmer and more widespread than all AR families (Fig. 11e). Collectively, the warm anomaly aligns with the anomalously high IWV and the negative geopotential height anomalies, all which extend from Hawaii to California (Figs. 11c–e). Many components, including the anomalously high IWV and negative geopotential height anomalies, helped contribute to the exceptional precipitation totals recorded in WY 2017.

One of the most impactful AR families during WY 2017 occurred over a 9-day period from 2 to 10 February 2017. The time evolution of the IVT field throughout this period clearly shows the multitude of AR events propagating across the Pacific (Fig. 12). Every day throughout this period, there is more than one AR associated with an independent EC or embedded mesoscale wave. This AR family led to the Oroville Dam
crisis in Northern California after the Feather River basin received as much as 690 mm of precipitation (White et al. 2019).

6. Conclusions and discussion

This study has argued that AR families are a distinct class of long-duration extreme events that bring extended periods of AR conditions. As discussed by Lamjiri et al. (2017) and Ralph et al. (2013), long-duration AR events may contribute to the accumulation of large precipitation totals and elevate streamflow, and therefore can be difficult to predict and manage (Vano et al. 2018; White et al. 2019). AR families are important to understand as they may increase flood risk, threatening property and disrupting lives. An example of the consequences of this elevated risk is the damage sustained to emergency and main spillways at Oroville Dam in Northern California that was exacerbated after an AR family affected the region. This study provides a definition of “atmospheric river families,” and evaluates relevant characteristics such as frequency of occurrence, seasonality, and intensity. The authors hope that by identifying and formally defining AR families, researchers, forecast meteorologists, and water resource managers can use this concept to develop situational awareness of the potentially elevated impacts of these high impact extreme weather events.

This study concluded that 47.80% of all AR events are associated with AR families. AR families, like AR events, most often occur in DJF, but there is large interannual variability among water years. California is known to have a variable climate, with ARs often bringing the state out of drought conditions and/or causing excess precipitation and flooding (Dettinger 2013). This study suggests that AR families might also play a large role in modulating which regime the state experiences. For example, WY 2017 experienced a record number of AR families, 26 total. The composite average of WY 2017 identified the presence of a persistent Rossby wave trainlike pattern in the middle and lower atmosphere. One hypothesized driver for that record breaking WY was the unusually high amount of moisture available for transport extending from the tropics to the California coast.

AR families can be described by their average synoptic conditions. They exhibit an anomalous low central geopotential height region off the coast of British Columbia at 500 and 850 hPa, a zonal and enhanced 250-hPa jet stream with a positive wind speed anomaly above BBY and higher IWV off the coast of California extending toward Hawaii. Compared to single AR events,
AR families are associated with lower geopotential heights across the North Pacific, higher geopotential heights over the subtropics, a stronger and more zonally elongated jet stream, and warmer tropical air temperatures. Multi-AR event AR families, those with more than three AR events, exhibit a larger negative geopotential height anomaly throughout the central Pacific. The positive 250-hPa wind speed anomaly, as in all AR families, is enhanced but for multi-AR event AR families is located more centrally in the Pacific and is stronger than dual-AR event AR families. Distinctly, AR families have multiple plumes of enhanced IWV originating from the tropics across the Pacific Ocean.

Furthermore, this common synoptic regime shows that AR families may be predictable. Based on an assessment of this regime using MERRA-2 reanalysis data, it is hypothesized that AR families occur due to areas of negative geopotential height anomalies situated in the middle of the North Pacific basin often embedded with multiple shortwave disturbances, which produce independent ECs, or mesoscale frontal waves affecting landfalling AR events. The equatorward extent of the low geopotential height region brings the shortwaves and frontal structures closer to areas of tropical moisture to entrain higher values of IWV. This synoptic regime shows that on average AR families develop in highly zonal flows, which may support the development of multiple AR events.

Understanding AR families dynamically and further evaluating their predictability potential can help water resource managers and dam operators as they try to ensure a sustainable water supply and mitigate flood risk. Future studies on AR families will investigate the regional and interannual variability associated with these storms, further explore dynamical drivers of these series of AR events and analyze the associated impacts including precipitation, soil moisture and streamflow. Investigating the identifiable synoptic patterns at different lead times, such as through the analysis of Rossby wave breaking or Rex blocking, could provide further insight into the predictability of AR families.

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Global Modeling and Assimilation Office. These data are available at MDISC, which is managed by the NASA Goddard Earth Sciences Data and Information Services Center. This work would also have not been possible without the Atmospheric River Observatory data provided by NOAA’s Physical Sciences Division, Earth System Research Laboratory, from their website at http://www.esrl.noaa.gov/osd/. We would also like to acknowledge high-performance computing support from Cheyenne provided by NCAR’s Computational and Information Systems Laboratory, sponsored by the National Science Foundation. The authors thank Drs. Art Miller, Jason Cordeira, and Forest Cannon for thoughtful discussions and internal reviews of this manuscript. Thank you to the anonymous reviewers who provided valuable comments and discussion.

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