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Hydrologic Impacts of Atmospheric Rivers on the Rillito Creek Watershed, 1979-2009

By

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Abstract

Atmospheric rivers are both a threat and a source of water to the western region of the United States. Drawing moisture from the Pacific Ocean, these long corridors of water vapor transport large quantities of water across the troposphere and serve as a critical source of precipitation throughout the cold season (October through March) in the Southwest, contributing specifically to Arizona's winter precipitation patterns. A previous study in Central Arizona has shown that atmospheric rivers are characteristically responsible for extreme precipitation and often lead to flooding that destroys public and private property and threatens lives (Demaria et al., 2017). As climate change increases sea surface temperatures, atmospheric rivers will likely intensify, worsening flooding conditions during the cold season. Pima County Regional Flood Control District is evaluating the impact of Atmospheric Rivers specifically on extreme precipitation in the Rillito Creek watershed in Tucson, Arizona. Precipitation data were analyzed from NOAA's Tucson International Airport rain gage and streamflow data from US Geological Survey stream gages over a 30-year observation period (1979-2009). NASA's Modern-Era Retrospective Analysis for Research and Application (MERRA) was used to identify the days during this 30-year span when an Atmospheric River occurred. The comparison between these days and days without ARs revealed that atmospheric rivers more frequently resulted in extreme precipitation events (exceeding the 98th percentile) in Tucson. We then discuss the impacts of climate change on flooding across the watershed.

Introduction

While climate change may sound like a simple warming of global average temperatures, studies show that without mitigation, climate change will have severe impacts on many of the resources upon which ecosystems and communities rely so heavily. One of these impacts affects the intensity of atmospheric rivers (ARs) through the warming of sea surface temperatures. Atmospheric rivers are responsible for transporting large quantities of water across the lower troposphere and play an important role in extreme precipitation events. The phenomenon mostly impacts west coasts of major land masses and is triggered by orthographic lift over mountains. With billions of dollars lost to the extreme flooding caused by these events, it is more important than ever to better understand, predict, and prepare for future ARs.

In a more local context, atmospheric rivers are a critical source of water for the arid and semiarid US Southwest. This is a region where water is often considered a commodity among natural ecosystems and settlements across the desert. The Colorado River serves as a critical source for the US Southwest but relies on ARs to support a policy that promises more water than what is available. While ARs can be helpful in terms of water resources, they still contribute to extreme flooding in the Southwest, and can be costly for property and natural habitats. This study intends to better understand how responsible ARs are for precipitation with an emphasis on extreme events. Previous studies conducted by the Pima County Flood Control District provide these details for the Salt and Verde River basins, but more work is to be done in the Tucson basin. In addition to its impact on flooding, we will also be studying how ARs affect the soil moisture, snow coverage, and precipitation phase in the region. In terms of the temporal boundaries of the study, we will be analyzing data from 1979 to 2009 and only at precipitation events that occur during the cold season.

Literature Review

Atmospheric rivers move across the troposphere to move large quantities of water from oceans to west coasts of major landmasses according to a study performed by Corringham et al. (2019). Rhoades et al. (2020) found that these atmospheric phenomena are responsible for 25-50% of precipitation that falls in the state of California; however, they are also the primary source of flooding across the west coast. Throughout 11 western states, this flooding cost up to $50.8 billion in damages from 1978 to 2017, and in some regions 99% of these flood events were credited to ARs. These calculations were made using data from insured loss which can likely underrepresent flooding in unexpected areas such as agriculture, infrastructure, and industrial plants. Unfortunately, even modest increases in AR intensity could severely impact these costs.

While atmospheric rivers occur with more frequency and for longer durations over the Northwest, they still impact the Southwest with a frequency that plays a more significant role than duration (Rutz et al., 2014). Arizona relies on both the Pacific Ocean and the Gulf of Mexico for moisture according to Karnieli and Osborn (1988). This precipitation occurs bimodally as summer monsoon stems from convective heating of tropical air and winter storms come from cold fronts. Winter frontal storms were determined to be more variable than the summer convective storms, and more dependent on the elevation and aspect of geologic features like the Mogollon Rim. A study by Demaria et al. (2017) focused on the impact of atmospheric rivers in the Salt and Verde River basins, two basins that are critical to Phoenix, Arizona's water supply. They also studied the impacts on snowpack and soil moisture in these basins, and how each of those impacted flooding. Demaria et al. concluded that atmospheric rivers contribute an average of 27% of total winter precipitation for these basins but disproportionately contributed to 68% of extreme precipitation where a quarter of events observed between 1970 and 2010 exceeded the 10-year return period. One event in 1982 perpetuated flood-enhancing characteristics of the soil by saturating it before a flood which took some lives and threatened the local economy (Demaria et al., 2017). However, Cao et al. (2020) determined that climate change and general warming is expected to mitigate these effects by reducing the initial soil moisture before storms. Cao et al. compared the soil moisture before and after storm-runoff events, a practice likely to be useful in our study.

The Tucson basin is surrounded by four mountain ranges which can intercept the moisture of atmospheric rivers (Rutz et al., 2014). While these mountains are not as obstructive as the Sierra-Nevadas to the north, Tucson relies more on atmospheric rivers that travel from the south over the Baja peninsula (Demaria et al., 2017; Rivera et al., 2014). Both studies identify these atmospheric rivers by characterizing patterns of vapor flux through integrated water vapor (IWV). Demaria et al. (2017) determined that changing the threshold for constituting an AR between 200 and 250 kg m^{-1} s^{-1} does not impact the spatial pattern but does impact frequency. Rutz et al. (2014) detected the water vapor using a Special Sensor Microwave/Imager (SSM/I) and was able to verify that spatial patterns were not impacted by this threshold, but they did see variations in magnitude.

Demaria et al. (2017) observed that despite greater precipitation in the summer, the greatest flows occur in March due to the accumulation of snowmelt becoming runoff, and greater evaporation rates in the summer. Rivera et al. (2014) and Guan et al. (2013) – the latter of whom conducted their study in the Sierra Nevadas – both determined that unusually large snowpack can be credited to relatively high frequencies of atmospheric rivers. Rutz et al. (2014) found that these frequencies are greatest in December, while Demaria et al. (2017) observed a peak in January. While Guan et al. (2013) were able to provide more certainty about how frequent ARs produced precipitation, they failed to find conclusive evidence pointing to average snow water equivalent (SWE) that precipitated in the Sierra Nevadas. This challenge will prove especially difficult for the study in the Tucson basin, considering that Demaria et al.'s (2017) study in the Salt and Verde River basins relied on nine SNOTEL sites to collect SWE data while the Tucson basin has none. With uncertainties associated with SWE and an absence of established sites to collect data this data, we will have to rely solely on precipitation data from NOAA and streamflow from USGS. However, Rutz et al. (2014) collected SWE using both SNOTEL and data from the Climate Prediction Center, the latter of which may be a sufficient method of quantifying snowpack.

Site Description

The general focus of our research was on the Tucson Basin (see Figure 1), more specifically the Rillito Creek watershed, which is a relatively flat watershed that encompasses the front range and base of the Santa Catalina Mountains. The delineation of the Rillito Creek watershed was initially limited by the extent of the digital elevation model (DEM) available from the Pima County Flood Control District. DEMs are developed by flying over a region and scanning the topography with light detection and ranging (LIDAR) remote sensing. While this method provides relatively high-resolution images, the LIDAR did not reach into the Coronado National Forest, which generally includes the Catalina mountain range north of Tucson (see Figure 2). The Rillito Creek gets much of its water from runoff coming off the front range of the Catalinas, which makes them an important feature to include in the GIS model. For this reason, we decided to use a DEM from the USGS instead, which provided an appropriate extent at the expense of weaker spatial resolution. Figure 2 also shows the location of two stream gages, one along the Rillito Creek, the other along Sabino Creek, and the rain gauge at the Tucson International Airport to the southwest.

Figure 1: Delineation of the Rillito Creek watershed in context of greater Arizona

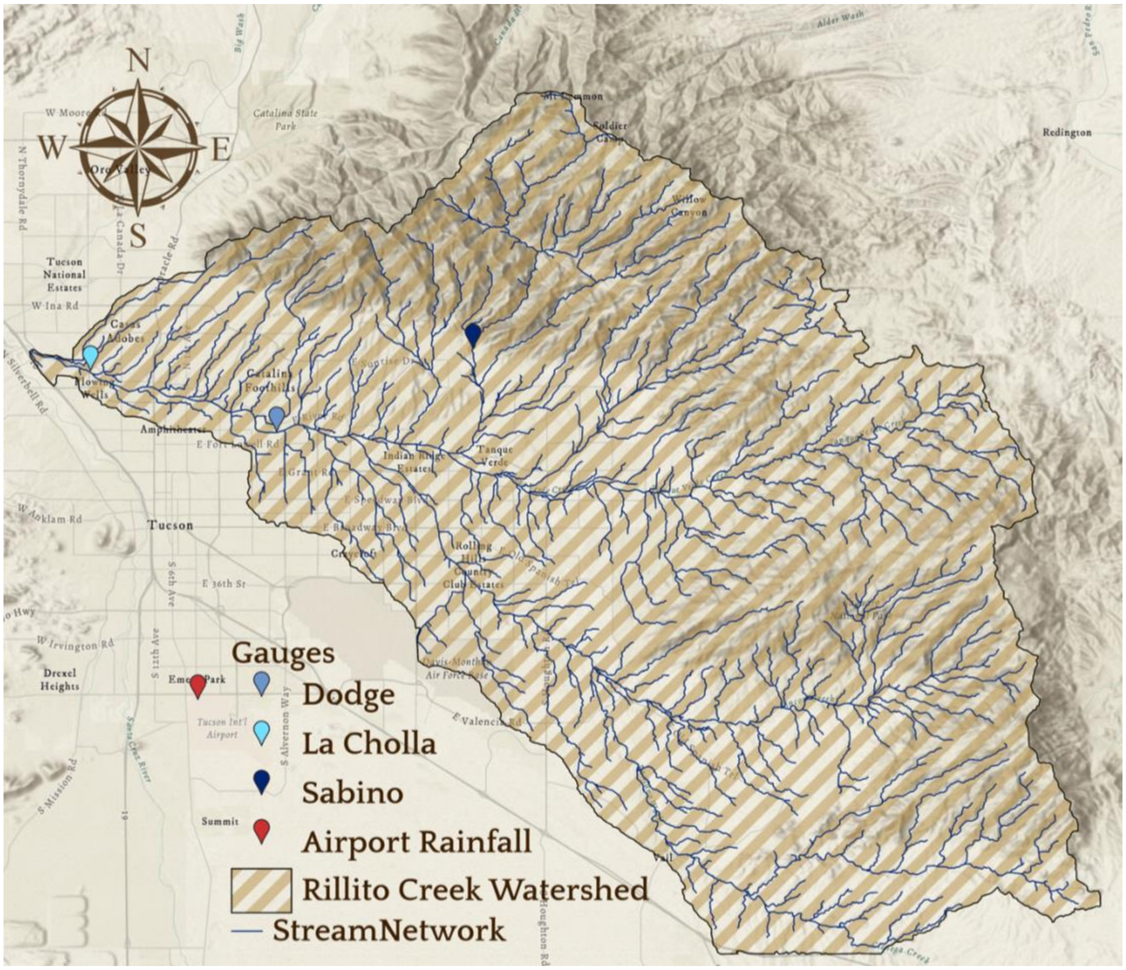

Figure 2: Delineation of the Rillito Creek watershed and stream network in Tucson, Arizona

Methods

Acquiring Data

The study relied on two data libraries for acquiring various physical, hydrologic, and atmospheric properties from 1979 to 2009. The first dataset, known as the Livneh et al. (2013) hydrometeorological dataset, was developed by the National Climatic Data Center (NCDC) and Cooperative Observer (COOP). The dataset was referenced for precipitation, temperature, SWE, and soil moisture data and features a 1/16° resolution. Additionally, the PRISM dataset, developed by Daly et al. (2013) provided daily precipitation and temperature information. To identify atmospheric rivers, the study called on NASA's Modern-Era Retrospective Analysis for Research and Application (MERRA) for atmospheric water vapor data.

Defining an Atmospheric River

MERRA was used to identify large fluxes of water vapor through the troposphere, which were measured as vertical integrated vapor transport (IVT) and were quantified using the following equation where QU is eastward flux and QV is northward flux.

$$IVT = \sqrt{QU^2 + QV^2}$$

In order to filter out vapor fluxes irrelevant to our data, to make the study comparable to similar studies, and to narrow our focus on extreme precipitation events, an IVT threshold was set to 250 kg m^{-1} s^{-1}. Qualifying atmospheric rivers also needed to have their leading edge within the boundaries of the Rillito Creek watershed and persist for at least 12 hours. An additional criterion required a 24-hour interval between qualifying ARs to further distinguish events. To quantify the impacts of these atmospheric rivers on the watersheds, each watershed was observed independently from the other. Impacts on precipitation were split into average rainfall (exceeding 50th percentile), heavy rainfall (exceeding 90th percentile), very heavy rainfall (exceeding 95th percentile), and extreme rainfall (exceeding 98th percentile).

Evaluating Impacts

To observe the impacts of atmospheric rivers on precipitation patterns, we compared statistics of precipitation that took place during and outside of atmospheric river events, categorizing rainfall into the aforementioned bins based on total depth precipitated per day. We also defined how much precipitation took place during an atmospheric river to evaluate its contribution to total precipitation. A similar approach was taken to evaluate the impacts on streamflow, yet drainage delays posed complications, prompting us to include the two days after the end of the AR event in our observation and crediting any precipitation towards this event.

Results

Across the extent of the observation period from 1979 to 2009, strictly observing precipitation in the cold season, atmospheric rivers contributed 36% of the precipitation. Figure 3 shows the contribution of atmospheric rivers to the total cold season precipitation from 1979 – 2009. The figure also shows the average number of AR days and includes a pie chart showing that ARs contributed 36% of the precipitation. There appear to be no definitive trends across the observation period, as peaks and valleys can generally be observed for the 30-year span. There are a few anomalies including a very large amount of non-AR precipitation in 1983, which was an El Nino year – arguably the most severe on record to date - that had a tropical storm make its way to Tucson (Lader, 2012). The 1999 cold season saw no precipitation but the two warm seasons (before and after) had large precipitation events within days of this cold season beginning and ending. Cold seasons from 1992 to 1994 were three consecutive years with high precipitation contributions from atmospheric rivers.

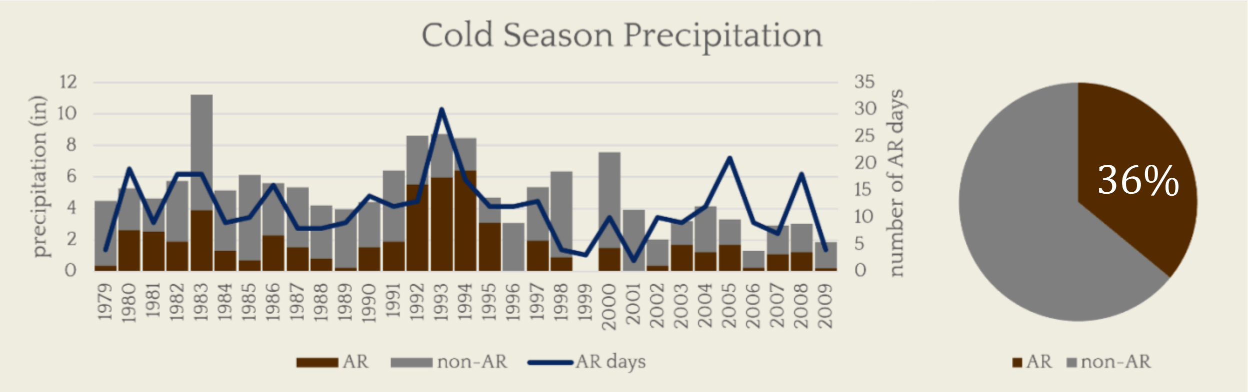

Figure 3: Characterization of AR contribution over cold season observation period and a pie chart showing cumulative contribution

Figures 4-7 depict the contribution made by atmospheric rivers, and are reported as precipitation depth, precipitation frequency, cumulative flow volume, and flow frequency, respectively. Extreme intensity is defined as the 98th percentile, very heavy as the 95th percentile, heavy as the 90th percentile, and average as the 50th percentile. Figures 4-7 show that AR-driven precipitation falls more often as high intensity events and more often leads to extreme streamflow.

The pie chart in Figure 3 showed that from 1979 to 2009, atmospheric rivers were 36% of the cumulative precipitation depth. However, Figure 4 shows that in the 95th percentile (i.e. the bar, labeled as very heavy), this contribution is as much as 47%. This skewness is greater in Figure 5 when evaluating the frequency of rain as opposed to rainfall depth. This skewness in AR contribution is amplified when changing our scope from rainfall to streamflow. Extreme streamflow particularly sees a gage average of 78% of its flow generated from atmospheric rivers as seen in Figure 6.

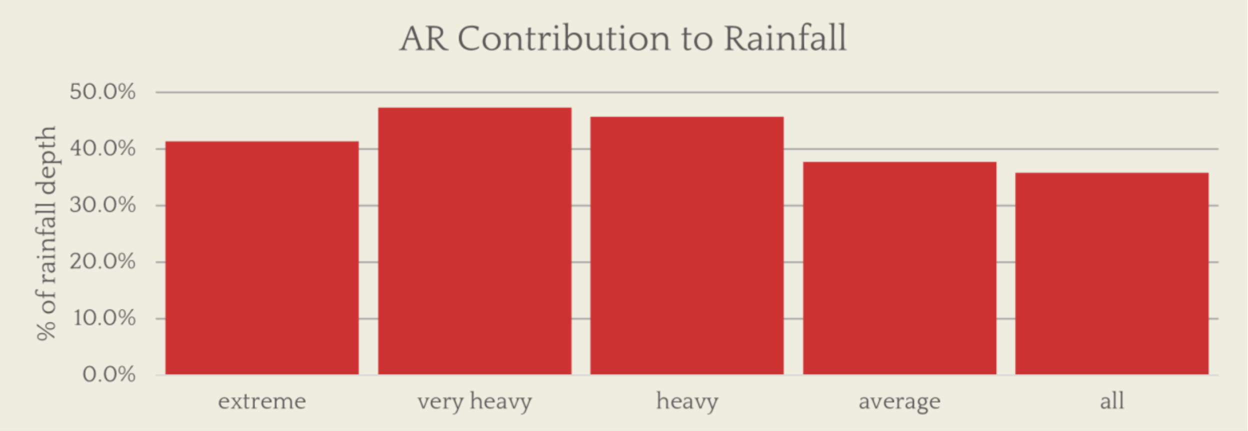

Figure 4: AR contribution to rainfall depth during the cold season from 1979-2009

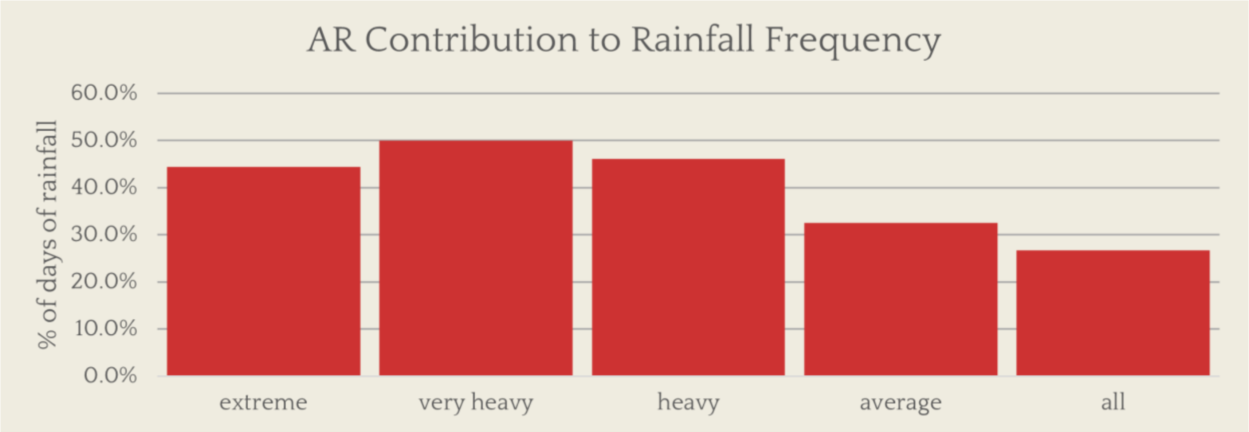

Figure 5: AR contribution to rainfall frequency during the cold season from 1979-2009

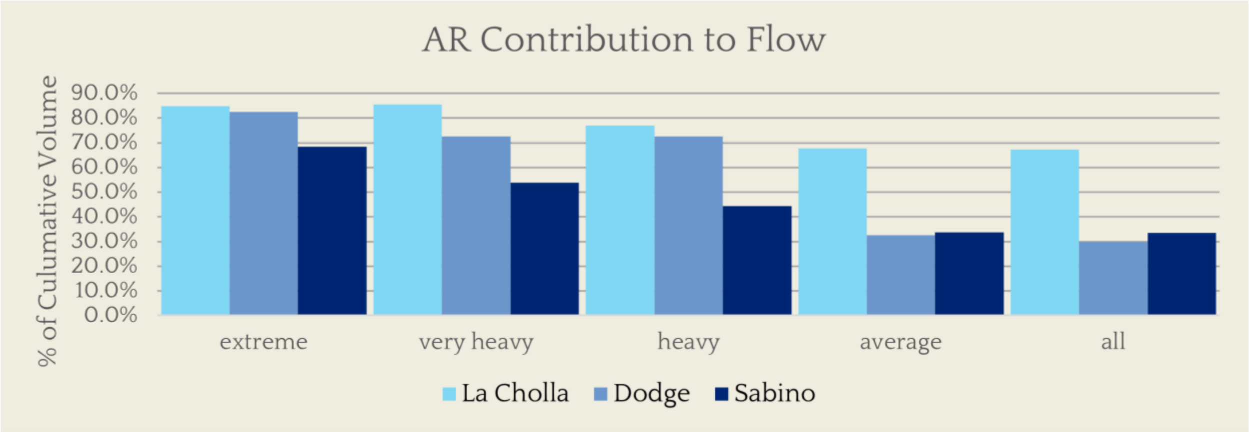

Figure 6: AR contribution to cumulative flow volume during the cold season from 1979-2009

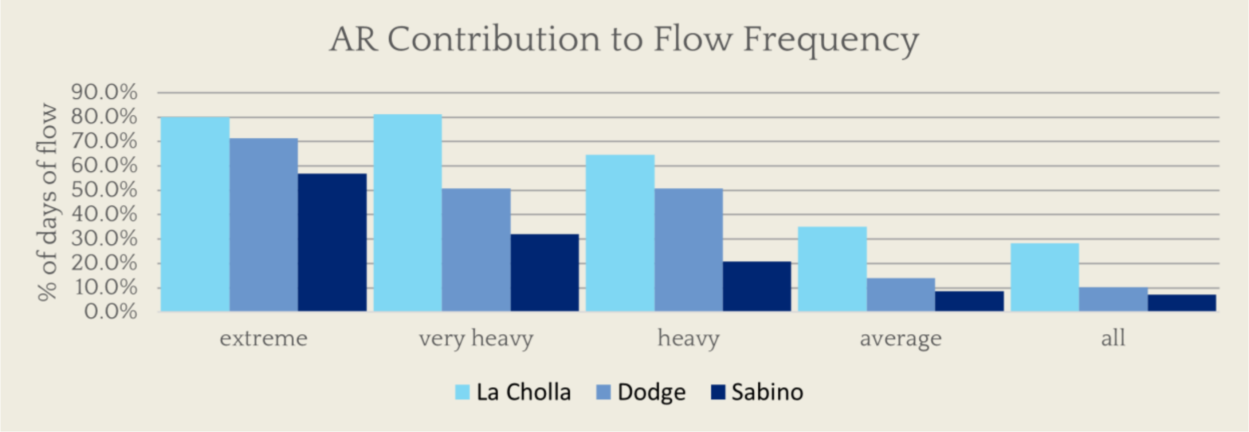

Figure 7: AR contribution to flow frequency during the cold season from 1979-2009

Conclusions

By observing Figures 4-7, we can see that AR-driven precipitation falls more often as high intensity events and more often leads to extreme streamflow. More specifically, Figure 5 shows that only 27% of all cold season precipitation events fall during an atmospheric river but when we narrow our observation to the 95th percentile (i.e., very heavy), atmospheric rivers will contribute up to 50%. This suggests that atmospheric rivers are a critical source of water resources and also a cause of flooding for the Rillito Creek watershed during the cold season. If we are to anticipate more intense atmospheric rivers in the future (e.g., owing to climate change), we must be prepared to see more than a third of precipitation depth increase in intensity (recall the pie chart in Figure 3 that showed ARs contribute 36% of the total precipitation). This disparity is amplified when observing streamflow. For example, Figure 7 shows that atmospheric rivers only contribute an average of 15.3% to days of flow but when only observing flow in the 98th percentile (i.e. extreme flow), atmospheric rivers will comprise an average of 69.5% percent of the days of flow. This presents a challenge to flood control to identify atmospheric rivers when they occur and prepare for flooding that tends to be more extreme than other rainfall delivery systems.

Future Research

There is still plenty to discover regarding the local impacts of atmospheric rivers. With the data we have now, we can begin investigating how often each cold season’s largest atmospheric river would repeat in the coming years. This analysis could help PC RFCD assess the frequency of floods and inform what measures should be taken in the foreseeable future. Additionally, the Rillito Creek covers a large area of Tucson, but it receives flow from a variety of locations like the Catalina Mountains to the north and the Sonoita Creek which is outside of the area we modeled for this study. Better understanding these watersheds and the way they are impacted by atmospheric rivers would certainly provide critical information to better understand how ARs contribute to water resources in Tucson.

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