AN ASSESSMENT OF ATMOSPHERIC RIVERS AS FLOOD PRODUCERS IN ARIZONA

by

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ABSTRACT

Atmospheric rivers (ARs) are a critical factor in the transport of water vapor to the mid-latitudes. Much of the existing research on the effects of ARs stress their importance as flood-producers in the Pacific Coast states of western North America, with the most focus on California and the impacts that ARs have on precipitation, flooding, and water resources in this region.

The objective of this study is to determine the importance and effects of ARs on flooding in Arizona and whether ARs have a greater impact on Arizona flooding than other Arizona flood-producing mechanisms, and the factors that affect AR activity and flooding. Analyses of AR fraction throughout Arizona showed that the distribution of AR activity in Arizona is limited to the Central Highlands region and not evenly throughout the state, and it is within this region that ARs have the most impact. For the regions of Arizona that were shown to be affected very little by AR events, the Colorado Plateau and the Basin and Range, the AR events that did occur in these regions did not influence the nature of flooding to the same degree that ARs in the Central Highlands did and their effects were nearly negligible. Another important finding of this study was how trajectory of a landfalling AR and the corridor in which the AR made landfall through can strongly affect which ARs will produce floods and which ARs will not.

1. Introduction

Atmospheric rivers (ARs) are long, narrow plumes of concentrated water vapor in the lower troposphere that are responsible for much of the horizontal moisture transport in the mid-latitudes (Zhu and Newell 1998). They produce extreme precipitation and major flooding events in the Pacific Coast states of the U.S. due, in part, to the orographic forcing of ARs over the coastal topography (Smith et al. 2010; Ralph and Dettinger 2012). In certain regions, such as California, ARs dominate the flood record and are responsible for the largest winter storms, and contribute greatly to the water resources of that area (Dettinger et al. 2011).

Atmospheric rivers can also penetrate inland and have been linked to precipitation and flooding in the interior of the United States, demonstrating that the influence of AR storms is not limited to west coast regions (Moore et al. 2012; Rutz and Steenburgh 2012; Rutz et al. 2014, 2015). Arizona, as California's neighbor to the east, has also been affected by precipitation and flooding associated with AR events in specific areas or watersheds (see Neiman et al. 2013; Rivera et al. 2014) but a large-scale regional assessment of the importance of ARs as flood producers in Arizona has not yet been done. Unlike the Pacific Coastal states where the cause of flooding is dominated by precipitation from synoptic-scale winter storms, Arizona's flood hydroclimatology is far less homogeneous. The flood record of Arizona includes events produced by non-AR and AR-associated winter synoptic storms, by localized or widespread summer convective storms, and by precipitation enhanced by the influx of moisture from Eastern Pacific tropical cyclones (see Hirschboeck 1987, 1988).

The goal of this study is to assess the importance of atmospheric river events as flood producers in Arizona watersheds, and explore how flood events that are produced by ARs compare to those produced by other mechanisms in terms of magnitude, region, and frequency. Specifically, this study will address the following topics:

1. Are certain regions in Arizona more susceptible or less sensitive to AR-related flooding?
2. Do ARs produce flooding events of greater magnitude than floods produced by other mechanisms?
3. What variables, if any, appear to affect the frequency, magnitude, and location of AR-related flooding?

2. Background and Motivation

Features now commonly referred to as “atmospheric rivers” were documented more than 50 years ago by Weaver (1962) as one of three different storm types that produced precipitation and flooding in California: the high-latitude, the middle-latitude, and the low-latitude. Weaver’s types were based upon the latitude at which the storms had initially formed. The low-latitude type storm, which develops near Hawaii and moves towards the Pacific West Coast, was a prototype for what became known as a “pineapple express” (PE) storm and today is understood to be a specific type of atmospheric river. Pineapple express events draw moisture from the tropics near Hawaii, affect the North American West Coast, and have been associated with heavy rainfall and flooding events in California (see Monteverdi 1995; Estes 1998). Prior to the advent of satellite observations, compilations of historically observed PEs have been the most consistent records of the atmospheric river events influencing the North American West Coast (see Dettinger 2004; Dettinger et al. 2011).

Satellites opened up a new way to observe these plumes of water vapor. Newell et al. (1992) produced a pilot study on the presence of filamentary structures in the atmosphere using data obtained from carbon monoxide measurements and the Total Ozone Mapping Spectrometer (TOMS). They called these features “tropospheric rivers”. The rivers persisted for a period of approximately ten days and had an eastward movement. Four to five of these rivers were present in both the Northern and Southern hemispheres moving into the mid-latitudes. Zhu and Newell (1998) studied water vapor fluxes in the troposphere and proposed a new algorithm and term to describe and identify these features: atmospheric rivers. They found that atmospheric rivers (ARs) cover less than 10% of the globe at any given time, but are responsible for much of the water vapor transport into the mid-latitudes. This study was one of the earliest to quantify the importance of ARs in the transport of water vapor across latitudes.

Studies in the last decade have focused on the impacts ARs have on precipitation and flooding in the Pacific Coast states of North America. Ralph et al. (2004) observed the characteristics and structure of an AR associated with a precipitation event in northern California. They found that this case study was representative of all AR events detected using Special Sensor Microwave Imager (SSM/I) and geostationary (GEOS) satellite data. This study also set the IWV value baseline of ≥ 2 cm for identifying ARs, a value that has held up in literature.

Neiman et al. (2008a) provided the first long-term characterization of the properties of ARs and their impacts in western North America, including the seasonality of ARs and the precipitation events associated with ARs from British Columbia to California. They looked at SSM/I composites for the period 1 October 1997 – 30 September 2005 and made observations of AR activity for the northwest coast (British Columbia, Washington, and Oregon) and the southwest coast (California). Their study found that the southwest coast experienced half as many days in which an AR was present than the northwest coast, and that ARs primarily occurred during the warm season in the north and the cool season in the south.

Dettinger et al. (2011) examined the AR days from Neiman et al. (2008a) and PE days going as far back as WY 1948, and assessed the precipitation and streamflow during and following these events with a focus on California. These events were found to contribute 20 – 50% of the state’s total precipitation and strongly influence both the water supply and flooding in California. This study showed how important AR events are for California’s water resources and the dominance they have in California’s precipitation and flood records.

Although these findings provide valuable insight into the behavior of AR events, Neiman et al. (2008a) and Dettinger et al. (2011) only looked at ARs making landfall at 32.5°N – 52.5°N in their studies. This range does not account for ARs crossing the west coast of the Baja Peninsula. Rutz and Steenburgh (2012) expanded on the findings of Dettinger et al. (2011) by including ARs as far south as 24°N, which significantly increased the AR fraction over the southwestern U.S. This increase suggested that ARs have a greater impact on precipitation in non-coastal western states, such as Arizona, than earlier studies would have suggested.

2.1 Inland Penetration

Neiman et al. (2013) presented the first detailed case study on the inland penetration of an AR from the Pacific Ocean into Arizona. This study demonstrated that ARs are capable of producing precipitation and flooding in Arizona, comparable to AR effects along the west coast of North America.

Rutz and Steenburgh (2015) named three trajectories of ARs (coastal-decaying, inland- or interior-penetrating), based on whether or not they stay as ARs over North America. They found that most inland- or inland-penetration ARs made landfall north of Cape Mendocino at low elevation corridors and passed to the north or the south of the high Sierras rather than directly. ARs making landfall through the Baja Peninsula were more likely to penetrate into the interior, but occurrence of these AR trajectories was less frequent. Other factors that affected the trajectories of ARs were the integrated vapor transport (IVT) value and increases in wind speed along the trajectory of the AR. Rutz and Steenburgh's identification of the Baja Peninsula trajectory, and the likelihood of ARs penetrating into the interior along this route, has great relevance for the ability of atmospheric rivers to produce flooding in Arizona.

Recent works have also linked ARs to extreme precipitation and flooding events outside of the United States. Viale and Nuñez (2011) studied winter orographic precipitation in the Andes during the period 1970 – 1976, and found that ARs were associated with 80% of the heaviest orographic precipitation events and AR storms produced twice as much precipitation as non-AR winter storms. Lavers et al. (2011) demonstrated that the ten largest winter flooding events in the United Kingdom since 1970 were associated with AR events. The works of Lavers et al. (2011) and Viale and

Nuñez (2011) show that the impacts ARs have on precipitation and flooding are not limited to only the U.S., and that ARs may pose a flooding hazard in every region they affect.

2.2 Atmospheric Rivers and Flooding

Atmospheric rivers have been linked to many precipitation and flooding events in the Pacific coast states of North America. Ralph et al. (2006) found that all flooding events that had occurred in the Russian River between October 1997 and February 2006 were associated with ARs, which showed how ARs can dominate some watersheds as the sole major flood producing mechanism.

Smith et al. (2010) modeled the behavior of an AR as it moves over terrain, comparing changes in water vapor flux, amount of precipitation, and location in which precipitation develops in three simulations where the terrain was variable. They found that there was a significant reduction in total precipitation when the terrain was completely removed, and precipitation seems to be driven primarily by orographic forcing and is limited to areas of sharp elevation. These results suggest that a key factor in why ARs can produce extreme precipitation and flooding is due to the orographic lifting of AR-related moisture over the coastal topography. Extreme precipitation and flooding may therefore be more likely to occur in watersheds that are affected by orographic precipitation.

Neiman et al. (2011) examined stream flow data collected from four major watersheds in western Washington with varying topographic characteristics. Their results showed that the surrounding topography of the watershed and the orientation at which the AR made landfall were influential in the flooding behavior of these watersheds. The watershed with the greatest direct exposure to the Pacific Ocean received the most consistent year-to-year peak flows, while the watershed that had a limited window of unobstructed terrain between it and the Pacific showed the most variability. The orientation at which the greatest peak flows occurred varied, depending on which orientation optimized the orographic control of precipitation.

Moore et al. (2012) presented a case study of an extreme precipitation event that had produced flooding in Tennessee and Kentucky. This event was associated with an AR that developed in the eastern tropical Pacific and was transported into the Mississippi Valley, which supported the production of two quasi-stationary mesoscale convective systems (MCS) and heavy precipitation over a fixed region. This study was one of the earliest on AR events that penetrated the interior of the U.S. and demonstrated that ARs could produce extreme flooding in areas far from the west coast.

Rivera et al. (2014) identified AR activity in the Verde River watershed from extreme precipitation events in that watershed and found two AR patterns affecting the Verde basin. They classified the ARs into two categories, Type 1 and Type 2, where a Type 1 AR obtains moisture from the tropics near Hawaii and has maximum moisture transport in the lower levels of the troposphere, and a Type 2 AR which has a more direct tropical origin and meridional orientation with maximum transport in the middle troposphere. Some AR events demonstrated a mixture of characteristics of both Type 1 and Type 2 ARs, which show that the two AR types are not mutually exclusive. By linking extreme precipitation events in the Verde River to ARs, this study documented AR activity in the Verde River watershed over a thirty-year period. However, Rivera et al. (2014) only looked at events in the Verde River basin, and since they only examined extreme precipitation, their study may not account for AR events that had produced non-extreme precipitation and flooding events.

Although research on AR events have shown that they impact regions beyond the eastern Pacific Coast and may be linked to extreme precipitation and flooding events in Arizona, no prior study has directly compared AR-related flood events that had occurred in the state to flooding events not associated with an AR. In addition, most of the AR-related flooding and precipitation events that have been studied are of extreme events while there has been little research on AR-related flooding or precipitation events that are not considered extreme.

2.3 Purpose

The purpose of this study is the assess the role of atmospheric rivers as flood producers in Arizona. The research will address both extreme and non-extreme AR-related flood events and assess how AR flood events compare to other flood-producing mechanisms in Arizona – not only with respect to extreme flooding, but also in terms of the importance of ARs as dominant or frequently occurring flood-producers. This assessment has the following objectives:

(1) To identify Arizona flood peaks that are associated with atmospheric rivers penetrating inland from the eastern North Pacific Ocean,

(2) To assess differences in the magnitude and frequency of AR flood peaks vs. non-AR related flood peaks in Arizona, and

(3) To analyze the spatial variability of AR flood influence in Arizona.

Table 1 outlines these steps, along with the procedures for accomplishing each objective.

This thesis is organized as follows. Section 3 describes the Arizona flood peak data and the sources of AR information that were used to compile a chronology of atmospheric rivers that affected Arizona and associate with these flood events. Section 4 explains a series of analyses used to evaluate the importance of ARs as flood producers, Section 5 explores factors that may explain the spatial variability of AR-associated flooding in Arizona, Section 6 discusses the results, and Section 7 summarizes the research conclusions.

3. Data and Physiographic Setting

In order to assess the importance of atmospheric rivers as flood producers in Arizona, a compilation of atmospheric rivers penetrating into Arizona was compared with a database of Arizona flood peaks to identify those peaks that may have been influenced by the ARs. The following sections describe the datasets used and the physiographic setting of the watersheds examined.

3.1 Arizona Flood Peak Data

The flood peaks used in this study were based on thirty-three gauging stations in Arizona (Figure 1, Table 2). The stations selected represent different physiographic and climatic regions of the state and are a subset of the stations included in the Arizona Flood Project Database (http://www.arizonafloodproject.org/). This database is an expansion and update of the original database of classified flood peaks developed by Hirschboeck (1987, 1988) in her study of flood hydroclimatology in Arizona. It lists peaks-above-base data (annual and partial duration peaks) observed at selected U.S. Geological gauging stations in Arizona. The peak flow data were obtained from published online data sources (http://waterdata.usgs.gov/az/nwis/nwis), from published annual USGS Water-Data Reports for Arizona, and directly from the Arizona Water Science Center, as needed. Each peak-above-base included in the Arizona Flood Project Database has been classified in terms of the flood-producing storm type or circulation pattern that generated the event (e.g. winter synoptic-scale precipitation, summer convective precipitation, tropical storm-enhanced synoptic-scale or convective precipitation). Atmospheric rivers affecting Arizona occur primarily in the cool season and are associated with synoptic-scale events, hence this study focuses mainly on flooding during the cool season months of November through April. In order to use a continuous record of satellite-based information to identify ARs (see following section), this study focuses on flood peaks observed at selected Arizona gauging stations having a complete period of record from 1 October 1987 – 30 September 2011. Stations with incomplete peak flow data during this time frame were not used, hence areas of the state with un-gauged watersheds or incomplete records are not well represented in this study.

3.2 Atmospheric River Data

The dataset of atmospheric river events used in this study was assembled by cross-referencing AR information from multiple sources (see Table 1). Several published studies of ARs that affected western North America provided an initial chronology of events to examine. The AR in these studies were identified by applying specific criteria to areas of concentrated water vapor in the atmosphere, based on measurements of either Integrated Water Vapor (IWV) or Vertically Integrated Horizontal Water Vapor Transport (IVT). IWV values represent the total amount of water vapor present in a vertical column of air, expressed as depths (e.g. cm) and can be estimated from SSM/I satellite data[1], from atmospheric reanalyses, or from models. (IWV can also be presented as Total Precipitable Water (TPW) in millimeters of liquid water). IVT values represent the overhead transport of water vapor at a gridpoint, expressed as fluxes in kg m^{-1} s^{-1}, and are calculated from atmospheric reanalyses or from models by integrating the horizontal moisture flux through a series of atmospheric layers (e.g., surface to 500 mb). Following is an overview of the published sources examined to develop this study's chronology of ARs affecting Arizona.

Neiman et al. (2008a) developed a chronology of landfalling ARs affecting the North American coast. They used SSM/I to identify narrow integrated water vapor (IWV) plumes with values > 2 cm that were > 2,000 km in length and < 1,000 km in width intersecting the western North American coastline between 32.5° – 52.5°N for the period 1 October 1997 – 30 September 2005. Dettinger et al. (2011) expanded upon this work, adding AR dates for 1 October 2005 – 30 September 2008 to Neiman et al.'s record and compiling a chronology of pineapple express events (PEs) affecting the western coast North America for the period 1 October 1948 – 30 September 2008. Rivera et al. (2014) focused specifically on Arizona and looked at extreme precipitation events in the Verde River basin during the cool season (November – March) for the period 1 October 1979 – 30 September 2011. They determined which of these precipitation events were associated with atmospheric rivers by defining an AR as an event satisfying the AR flux algorithm by Zhu and Newell (1988) with integrated vapor transport (IVT) > 250 kg m^{-1} s^{-1} and length >2,000 km. Using these criteria, they put together a record of extreme precipitation

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[1] Special Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Imager Sounder (SSM/IS) instruments onboard the Defense Meteorological Satellite Program (DMSP) satellites

events in the Verde River basin that indicated whether or not each event was associated with an AR.

The AR events recorded in the above studies were then cross-referenced with an independent compilation of ARs developed for this project based on composite images of Integrated Water Vapor (IWV) and Total Precipitable Water Vapor (TPW) from satellite imagery (SSM/I data) and a gridpoint dataset of Vertically Integrated Water Vapor Transport (IVT) associated with ARs over Arizona that was kindly provided by Jonathan Rutz and James Steenburgh (personal communication, 2013). Details on these IWV and IVT datasets follow.

3.2.1 Integrated Water Vapor (IWV) Data from SSM/I

Daily Integrated Water Vapor (IWV) composite images derived from Special Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Imager Sounder (SSM/IS) instruments onboard the Defense Meteorological Satellite Program (DMSP) satellites were used to identify ARs with trajectories aimed toward Arizona and likely to penetrate inland. The images were obtained online from Remote Sensing Systems[2] (www.remss.com) and were examined to determine the presence or non-presence of AR patterns prior to or during each of the flood peaks at the study gauge in the Arizona Flood Project Database. The composites, available at http://images.remss.com/ssmi/ssmi_data_daily.html, are produced every twelve hours, when satellites complete one pass. SSM/I data were available on this site beginning in late 1987. This determined the starting hydrologic year or water year (WY), which begins in October and ends in September of the following year, for the study period. Figure 2

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[2] SSM/I data provided by Remote Sensing Systems are sponsored by the NASA Earth Science MEaSUREs DISCOVER Project

shows an example of one of the composite images used. Appendix A contains all composites evaluated for the study period of 1 October 1987 – 30 September 2011.

3.2.2 Vertically Integrated IVT Grid Point Measurements

Rutz and Steenburgh (personal communication, 2013) identified ARs that occurred in the cool season months (November – April) for the period 1 October 1988 – 30 September 2011 with the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim; Dee et al. 2011). They classified precipitation as AR-related if an AR had been identified at the closest ERA-Interim grid point at any of the reanalysis times. With a spatial resolution of 1.58 latitude x 1.58 longitude and a temporal resolution of 6 hours, the Rutz and Steenburgh IVT gridpoint dataset made available to us provided a way to connect AR influence with the occurrence of peak flows in Arizona watersheds throughout the state, representing different hydroclimatic and physiographic regions. Rutz and Steenburgh identified ARs objectively as either (1) a region >2,000 km long with IWV > 20 mm, or (2) a region >2,000 km long with integrated vapor transport value (IVT) > 250 kg m^{-1} s^{-1}.

3.3 Arizona AR Days

An initial examination of eastern North Pacific ARs in SSM/I imagery approaching California and northwest Mexico during the period 1 October 1987 – 30 September 2011 indicated that ARs associated with peak flows in the Arizona Flood Hydroclimatology Database preceded the actual peak flow by no more than two days. Prior to a peak flow occurrence, AR plumes intersected the North American continental boundary within an area bounded by 25°N – 35°N and 110°W – 130°W. On this basis, an Arizona AR Day, as defined in this study, is a day on which an AR pattern in the SSM/I with IVT > 2 cm, length > 2,000 km, and width < 1,000 km was observed in the eastern North Pacific Ocean during at least one twelve-hour satellite passing period in the region specified above. This definition is based on a review of the most common AR definitions found in the literature (Table 3). All SSM/I composites available for the study period were reviewed to identify the days that met the Arizona AR Day criteria. Cross checking the AR Days with flood information in the Database allowed the determination of which flood events, if any, appeared to be associated with ARs.

As an independent check, the Arizona AR Days were then compared with AR dates already compiled in the works of Neiman et al. (2008a), Dettinger et al. (2011), Rivera et al. (2014), and Rutz and Steenburgh (personal communication). All dates from each source were combined into a master chronology of AR events and integrated in the Arizona Flood Project Database to identify the ARs associated with flooding in Arizona and those that were not associated with flooding. Lastly, watershed maps were produced to show which gauging stations recorded flood peaks in response to the flood-associated AR events. Figure 3 illustrates this procedure and Appendix A contains an annotated AR image gallery for the chronology of AR Days compiled in this study and associated watershed maps that indicate where ARs produced flooding during the study period.

3.4 Physiological and Climatic Setting

Previous work has pointed to the importance of orography as a factor in the precipitation and flooding associated with atmospheric rivers (Smith et al. 2010; Neiman et al. 2011). To assess the role of orography on atmospheric rivers and flooding in Arizona, an understanding of the physiographic setting of the state as it interacts with different types of seasonal precipitation-delivery systems is needed. Arizona can be divided into three main physiographic regions: the Colorado Plateau in the north, the Basin and Range Province in the south and west, and the Central Highlands Transition Zone between these two areas (Figure 4). The Colorado Plateau is a flat, high-elevation semiarid region in northern and northeastern Arizona. It receives much of its precipitation during the summer from convective storms and the winter from synoptic winter storms. Few AR-related flooding events have been observed in this region. The Basin and Range Province makes up most of southern and western Arizona and consists of alternating regions of steep linear mountain ranges and flat desert. The semiarid southeastern region is considerably more mountainous than the extremely arid southwestern region. The region receives both AR and non-AR winter synoptic precipitation and flooding, but the most common flood-producing mechanism in this region is summer convective rainfall and the largest floods are associated with infrequent tropical storms (Hirschboeck 1987, 1988). The Central Highlands Transition Zone is comprised of mountainous terrain and valleys of varying elevations. The Mogollon Rim, an escarpment that runs from the northwest to the southeast across the region is a prominent orographic feature associated with an abrupt increase in elevation. Precipitation and flooding in the Central Highlands is dominated by AR and non-AR winter synoptic storms, although summer convective and tropical storms also produce some flooding. Precipitation and flooding events in the Central Highlands Transition Zone can be especially extreme in this region due to the great orographic effect observed in this area.

4. The Importance of ARs as Flood Producers

To analyze the role and importance of atmospheric rivers as flood producers in Arizona, it is necessary to determine the yearly distribution and flooding behavior of AR events throughout the state.

4.1 Interannual Variability and Seasonality of ARs

Table 4 displays the number of Arizona AR Days occurring during the cool season months during 1 October 1987 – 30 September 2011, and indicates dates when an AR was associated with a flood peak in the Arizona Flood Project Database. Figure 5 shows the monthly distribution of AR-related peaks, and Figure 6 shows the interannual variability of AR events. The chronology of AR events during the period of record show no significant trends over time in the number of peak-producing events, non-peak events, or the total number of events. What it does reveal is that AR activity was present during every year in the study period (Table 4, Figure 6). Even in years where there was minimal or no AR-related flooding, a nonzero number of non-flooding AR events were observed.

Flood-producing AR events are linked predominantly to the cool season months. These findings support the work of Neiman et al. (2008a), which stated that ARs had occurred primarily during the warm season in the northern west Pacific coast and during the cool season in California. During the summer months ARs primarily affect regions at higher latitudes, whereas wintertime ARs can extend to lower latitudes than would be possible for summer ARs. No AR-related peak flows were present in the summer for this study because all summertime ARs during the period of record were shown to have occurred at too high a latitude to have affected Arizona in the SSM/I.

Peak flow dates associated with ARs occurred throughout the period October – May with the highest number of flood-producing events observed in the three-month period of January – March. The sole AR event in May had occurred near the end of April and was the latest AR observed during the period of study, which suggests that peak AR activity in Arizona is during October – April and the May event was more of an anomaly.

A comparison of the monthly distributions of all AR-related peak flows observed during the study period shows that the pattern of monthly AR flooding is similar for the three physiographic regions of Arizona (Figure 5). The number of peak flows increases until January for all regions and then declines in the last months of AR activity.

Throughout 1 October 1987 – 30 September 2011 at least one AR event had occurred every hydrologic year, but not every AR was associated with flooding. There were some hydrologic years in which no AR-related peak flows were observed. No clear pattern appears to be present as to which years had greater AR activity, although El Niño may play some role (Table 4, Figure 6). During an El Niño, the southwestern U.S. and northwest Mexico experience increased precipitation and wetter winters. AR events that occurred during warm El Niño periods, obtained from http://ggweather.com/enso/oni.htm and http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml, had a greater tendency to produce flooding than events that had not, but this observation is not decisive enough to say whether El Niño makes a difference in AR flooding.

One observation that can be made with respect to the yearly AR frequency is that years with a high frequency of occurrence of AR events penetrating into Arizona also tend to be years in which many ARs actually produce floods, instead of being "non-flooding AR events." This suggests that antecedent conditions in the watershed play an important role in flooding, and that if AR events occur in constant succession to one another it is more likely for flooding to occur as a result of later AR storms. The widespread extreme flooding throughout Arizona in winter 1992 – 1993 was associated with multiple ARs impacting the state over a 4-month period (see discussion of the these record-breaking floods in House and Hirschboeck, 1997). Other high-frequency AR years that produced a high frequency of AR flooding occurred in 1991, 1995, 1998, and 2005. Most – but not all – of these were associated with a weak, moderate or strong El Niño (see Table 4).

There are some years on record in which there was very little or no AR-related flooding but high AR activity. Some possible factors as to why certain ARs may produce flooding and others do not will be discussed further in Section 5. The lack of flooding events associated with certain ARs is also telling in of itself, as it shows that not all AR events will produce flooding.

These results show that flooding associated with ARs is a seasonal occurrence in Arizona to the point of exclusion for some months (June – September). For these months, ARs are all but absent in Arizona as a flood-producing mechanism. Even during the months in which AR activity is present, AR events and AR-related peak flows are not distributed evenly.

4.2 AR Fraction

To measure the importance of AR-related flooding within specific watersheds in Arizona, AR fraction was used as an indicator. Originally used by Rutz and Steenburgh (2012) to assess the fraction of the cool season precipitation produced by a landfalling AR compared to all precipitation, for the purposes of this study the AR fraction is the proportion of peak flow events associated with AR events compared to all peaks observed at a given gauging station during the study period. To find the AR fraction at select gauging stations throughout Arizona, the following equation was used:

$$AR\ fraction = \frac{total\ AR\ peaks}{total\ observed\ peaks} \tag{1}$$

The AR fraction was calculated for each station based on (1) annual peaks, and (2) all partial duration series “peaks-above-base” observed at that station and are listed in Table 2. High AR fraction values indicate that the watershed above the station was AR-sensitive, while lower AR fractions indicate that AR-related floods were infrequent in that watershed.

The annual and all peaks-above-base AR fractions are grouped geographically and by physiological region in Figure 7. The five stations in the Little Colorado, Upper Colorado, and San Juan watersheds were combined to represent the Colorado Plateau region due to a shortage of gauging stations in these watersheds. Stations located in the Gila, Verde, Salt, and Agua Fria watersheds showed higher AR fractions compared to AR fractions for stations in the Santa Cruz, the San Pedro, and the Colorado Plateau. The Gila, Verde, Salt, and Agua Fria watersheds are all located in the Central Highlands Transition Zone; the Santa Cruz and San Pedro are in the southeastern Basin and Range Province. The implications of these results suggest that merely the presence of an AR does not produce flooding in a watershed, nor are all watersheds affected equally by an AR. It also suggests the watersheds in the Central Highlands have some characteristic that makes them more favorable to AR-related flooding.

4.3 Magnitude of AR and non-AR Flood Peaks

To compare the discharge magnitudes of peak flows associated with ARs to those produced by non-AR events the peak discharges were transformed to dimensionless z-scores to facilitate station-to-station comparisons for drainage areas of varying sizes. The z-score of a peak flow at a given station was obtained using:

$$z = \frac{x - \mu}{\sigma} \qquad (2)$$

where x is the $\log_{10}$ value of the discharge of that peak, μ is the mean of that station, and σ is the standard deviation of that station.

There were regional patterns in the average z-score values calculated for AR-related floods vs. non-AR-related floods, as well as for floods occurring at other times of the year due to convective storms (see Appendix B). All stations located in the Central Highlands Transition Zone show positive average AR z-score values for both annual peaks and all peaks-above-base. For all but one station, (#15), the AR peaks have a higher z-score value than floods produced by any other mechanism. Because most of the stations with records suitable for this study are located in the Central Highlands, the AR influence in this region is well documented and robust.

The stations in the Colorado Plateau and southern Basin and Range Province observed fewer AR-related peaks, and in many cases fewer winter peaks in general. Because of the lack of data, there is far less consistency in the z-scores calculated for these regions so any region-wide conclusions about the magnitude of AR floods vs. non-AR floods are less reliable in these areas.

4.3.1 AR Influence on Rank of Peak Flow Events

In order to evaluate whether the largest peak events observed at a station were more likely to be associated with ARs than other flood-producing mechanisms, a Pearson's chi-square test was performed on a subset of watersheds. The test evaluated whether or not there was a statistically significant relationship between the ranking of a peak and the mechanism that produced it. The test was done as follows.

All the peak flows observed at selected gauging stations in the Gila, Verde, Santa Cruz, Little Colorado, and Salt watersheds were organized into contingency tables. The peaks were separated by the mechanism that produced them and their ranking (top, middle, or bottom) in a given watershed. A contingency table was then used to categorize each peak by mechanism and whether it ranked in the top third, middle third, or bottom third for that watershed. Table 5 shows an example for Stations #7, 11, and 12: the Gila below Blue River near Virden, the Gila near Solomon, and the Gila at Calva.

The chi-square test statistic was calculated as follows:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \qquad (3)$$

where O_i is the observed frequency, E_i is the expected frequency, and *n* is the number of cells. The expected frequency of a cell was found using the following equation:

$$E_i = \frac{r_i c_j}{n} \qquad (4)$$

where r_i is the total observations for row *i*, c_j is the total observations for column *j*, and *n* is the total number of observations. The number of degrees of freedom was found using:

$$df = (r - 1)(c - 1) \tag{4}$$

where *df* is the degrees of freedom, *c* is the total number of columns, and *r* is the total number of rows.

This test was performed twice – once using the actual discharge value (in cubic feet per second) to rank the peak flows in a watershed, and again using the z-score values of discharge to rank them. The ranking by actual discharge and z-score was used to check on whether changing the way discharge was measured would have an effect on the chi-square test statistic. Comparing the actual discharge of the peaks in a watershed reveals how large the flooding produced from a storm was, but it does not indicate whether or not the peak flow produced was large with respect to the gauging station mean.

The value of the chi-square test statistic was calculated from the contingency tables for each of the five watersheds using both the direct discharge magnitudes and the z-scores of discharge (Table 6 shows an example for actual discharge; see Appendix C for all results). The chi-square test statistic indicates that there is sufficient evidence to reject the null hypothesis that peak ranking and mechanism of peaks are independent. These results show that there is some difference in the ranking of peak flows by mechanism in the Verde and Gila watersheds, but it does not indicate whether the AR peaks are greater in magnitude than peaks produced by other means.

The Santa Cruz watershed shows that at a 0.010 significance level there is not sufficient evidence to reject the null hypothesis that the magnitude of the peaks and the mechanism of the peaks are independent for either the direct discharge or the z-score of discharge. The results show that in the Santa Cruz watershed the ranking of peak flow events by the type of storm that produced them are consistent. There is no evidence to suggest that a certain mechanism is more likely to produce peaks of greater magnitude than other flood-producing mechanisms.

Results for the Salt and Little Colorado watersheds show that the significance of the chi-square test statistic values for these watersheds is dependent on which method was used to determine ranking. For the Salt watershed, at the 0.010 significance level there was sufficient evidence to say that the direct discharge and the mechanism of the storm that produced the peaks were not independent, but the test statistic comparing the z-score of discharge and the storm type did not indicate that the factors were dependent. Likewise, in the Little Colorado watershed, at the 0.010 significance level the direct discharge and the flood mechanism were independent. But the z-score of discharge and storm type were shown to not be independent of one another.

These results suggest that in the Verde and Gila basins the ranking of the magnitude of peak flows within those watersheds is dependent on the storm that produced them, and that different flood mechanisms may produce larger or smaller peaks compared to one another. For the Santa Cruz watershed, there is no indicator that storm type affects the magnitude of peak flows produced in that watershed. The results for the Little Colorado and Salt watersheds are mixed, suggesting that further study requiring more information needs to be done for these watersheds.

Both the Verde and the Gila watersheds are located in the Transition Zone, which suggest that the magnitude of flood events in this region may be tied to the flood mechanism that produced them. If this assumption holds true, it would allow for better understanding of the flooding behavior in this region and better preparation for large storm and flooding events.

4.3.2 Difference in Means of AR and Non-AR Peaks

To determine the difference in means of AR-related peak flows to non-AR winter and convective peaks, a two-sample t-test was performed at select gauging stations comparing the means of peaks produced by AR events to non-AR winter storm peaks, and the means of AR-related peak flows to those produced by summer convective storms.

The means of the lognormal values of discharge at selected gauging stations for events produced by each of the flood-producing mechanisms were computed and the test statistic was calculated using the following equations:

$$t = \frac{x_1 - x_2}{s_{x_1 x_2} \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{6}$$

$$t = \frac{x_1 - x_2}{s_{x_1 - x_2}} \tag{7}$$

where x_1 and x_2 are the means of the peaks produced by different mechanisms, *n* is the sample size, and *s* is the standard deviation, found using:

$$s_{x_1 x_2} = \sqrt{\frac{(n_1 - 1)s_{x_1}^2 + (n_2 - 1)s_{x_2}^2}{n_1 + n_2 - 2}} \tag{8}$$

$$s_{x_1 - x_2} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \tag{9}$$

Eq. (5) and Eq. (7) were used to calculate the value of the t-statistic when the variances of the two sample populations were similar. If the variances were not similar, then Eq. (6) and Eq. (8) were used to find the t-statistic. To test whether the variances of the two populations were similar or not similar, the following ratio was used:

$$\frac{Larger\ s^2}{Smaller\ s^2} > 3 \tag{10}$$

where the variances are considered to be similar if the ratio is not greater than 3, and not similar if the ratio exceeds 3.

The two-sample t-test determines whether there is sufficient evidence to say that a difference in the means of AR-related peak flows and non-AR peak flows exists. If none of the stations show a difference in the means of AR and non-AR peaks, it cannot be concluded that ARs produce storm and flooding events of greater magnitude than non-AR flood-producing mechanisms. If there are stations that show a difference for one or both comparisons of the means, it suggests that the mechanism that produced a storm or flood event and the magnitude of flooding produced by that event may not be independent.

To find the difference in the means of AR-related peak flows and non-AR peak flows at select gauging stations, the mean and standard deviation for the lognormal discharge at each station were found and the t-statistic for the means of AR-related peaks versus non-AR winter and convective peaks at the selected stations was calculated (Table 6). The t-statistic values were compared at a 0.010 significance level. Because both types of comparisons (AR vs. non-AR winter, AR vs. convective) throughout all gauging stations vary in degrees of freedom, there was no one consistent rejection region. The value of the rejection region for each of the stations and the degrees of freedom were found in order to test the significance of the t-statistic values (Appendix D).

The results are shown in Table 7 for the difference in means of AR vs. Non-AR winter synoptic peaks and for AR vs. summer convective peaks. In all cases, the AR-related peaks were of greater magnitude than the non-AR winter peaks and the summer convective peaks. All of the stations that showed a significant difference in the means of AR versus non-AR winter or convective peaks were located in the Central Highland Transition Zone.

The gauging stations analyzed that were located in the Colorado Plateau or the southeastern Basin and Range regions did not show a significant difference in means between AR vs. Non-AR floods. The results for these gauging stations are in agreement with the chi-square test statistic, in which the Santa Cruz watershed showed no relationship between magnitude of peak flow and flood-producing mechanism and the Little Colorado result was inconclusive.

All of the statistical analysis results indicate that although ARs may not be universally the largest flood-producing mechanism at every gauging station in every watershed, they dominate the flood peak record in the Central Highlands Transition Zone and are responsible for some of the largest winter storms that have occurred. The watersheds in this region are the most sensitive to AR activity and most likely to observe large AR-related flood events. The stations in the northern Colorado Plateau and the southern Basin and Range regions recorded very few AR-related floods throughout the period of record. The AR-related peaks that did occur were not significantly larger than flooding produced by other mechanisms. Therefore these regions appear to be far less AR-insensitive and are the least likely to experience major AR flood events.

Because there were no gauging stations in far western and southwestern Arizona in this study, the flooding and AR behavior in those areas cannot be inferred from the results of this study and further research into the influence of atmospheric rivers on flooding behavior of western Arizona is needed.

5. Explorations of Factors that May Influence the Spatial Variability of AR Flooding

The dominance of the AR influence in the Central Highlands watersheds prompted further exploration on possible reasons for this spatial variability.

5.1 Basin Characteristics

The possibility that certain basin characteristics might have an influence on the watersheds in which AR flooding dominates was investigated with data obtained from the US Geological Survey's StreamStats website.(3) The basin characteristic variables evaluated were: the percentage of slope greater than 30°, mean basin slope, outlet elevation, maximum elevation, drainage basin size, percentage of forest cover, and soil permeability. Basin characteristic values for the area above the study gauging stations were plotted against the corresponding AR fraction for that gauging station to see if there was any correlation between AR fraction and the selected basin characteristic variables. Figures 8-14 are plots of AR fraction against basin characteristics for the study gauging stations and reveal some interesting hints as to why some basins are more responsive to flooding by atmospheric rivers than others.

The AR fraction of gauging stations located in the Central Highlands and the Basin and Range appeared to have no relationship with the area of the corresponding drainage basin. However, the AR fraction measured at stations in the Colorado Plateau seemed to increase slightly with the basin area. Comparing the AR fraction to maximum elevation showed no trend in the Central Highlands, but stations in the Colorado Plateau and the Basin and Range demonstrated a tendency for AR fraction to increase with the maximum elevation to varying degrees. When the AR fraction was compared to the outlet elevation, stations located in all three physiographic locations decreased in AR fraction as the outlet elevation increased.

Comparing the percentage of slope greater than 30° and the mean basin slope to AR fraction showed no noticeable trends for the Central Highlands and the Colorado Plateau stations. The Basin and Range gauging stations, on the other hand, increased as the percentage of slope greater than 30° and the mean basin slope increased.

Stations in the Central Highlands tended to increase in AR fraction along with the permeability of the soil. The Colorado Plateau gauging stations demonstrated very slight decrease in AR fraction in response to increased permeability, while the Basin and Range stations showed no trend. When the percentage of forest cover was compared to the AR fraction, stations in both the Central Highlands and the Basin and Range showed that the AR fraction tended to increase as the percentage of forest cover increased while stations in the Colorado Plateau did not demonstrate any noticeable trend.

Further study into the basin characteristic variables that may affect flooding in Arizona watersheds, especially for the watersheds in the Central Highlands Transition Zone, is required.

6. Discussion

The objective of this study was to assess the importance of atmospheric rivers as flood producers in Arizona, and the role ARs played in Arizona flood events compared to that of other Arizona flood producing mechanisms. The following research questions had been stated in the introduction:

1. *Are certain regions in Arizona more susceptible or less sensitive to AR-related flooding?*

There are certain regions and watersheds in Arizona that were more sensitive to AR-related flooding. Of the three physiographic regions, the AR fractions of stations in the Central Highlands Transition Zone had the highest values for both annual peaks and all peaks-above-base. The AR fractions of this region ranged from 0.292 – 0.542 (annual) and 0.257 – 0.57 (all peaks-above-base), and outranked all but one of the AR fractions observed at gauging stations in the other two physiographic regions.

The distribution of AR-related flooding in the Central Highlands, however, is not homogeneous. Variability was observed in the Central Highlands AR fractions, and this variability appeared to be linked to the watersheds of this region. The Gila watershed is in the eastern Central Highlands, and the AR fractions of gauging stations in this watershed were on average smaller than those of the Salt and Verde, which are located in the center of the Central Highlands. These results imply that certain watersheds and regions within the Central Highlands have more favorable variables and conditions for producing AR-related flooding events compared to other parts in the same physiographic region.

In contrast, the Colorado Plateau and the Basin and Range Province regions are AR insensitive. The AR fractions observed at gauging stations in these regions are much smaller than what was observed in the Central Highlands – ranging from 0.042 – 0.167 for the annual AR fraction for both regions, 0.056 – 0.162 for all peaks-above-base in the Colorado Plateau, and 0.03 – 0.286 for the Basin and Range Province. This shows that the majority of Arizona AR activity manifests in the Central Highlands, and that ARs are not a dominant flood-producing mechanism in the Colorado Plateau and the Basin and Range Province.

The seasonality of AR events and AR-related flooding events throughout the three Arizona physiological regions is consistent. ARs and AR-related flooding were observed only in the cool season months of October – May, and were absent entirely in Arizona in the months of June – August. This result is in agreement with the findings of Neiman et al. (2008), which stated in a study of landfalling ARs along the western coast of North America that most ARs had occurred during the cool season in the south (the California coast, from 32.5°–41.0°N).

2. *Do ARs produce flooding events of greater magnitude than floods produced by other mechanisms?*

A comparison of z-scores for peak flow events throughout the selected watersheds showed that in the Central Highlands, the z-score calculated for AR-related peak flows had an overall positive trend throughout all Central Highlands gauging stations for both annual peaks only and all peaks-above-base. With the exception of Station #15, the AR z-scores outranked the z-scores of the other flood-producing mechanisms for both annual and all-peaks-above-base in the Central Highlands. These results imply that in this region the peak flows produced by AR-related events tend to be greater than those produced by other mechanisms. It also demonstrates a strong consistency in behavior throughout all

Central Highlands stations, and suggests that regardless of variability in AR fraction and z-score value of these stations there is an overall similarity in flooding behavior within this region.

The Colorado Plateau and Basin and Range z-scores show far less consistency in flooding behavior throughout each region. There was no one flood-producing mechanism in which the z-scores for that mechanism consistently outranked the z-scores of the other flood-producing mechanisms for either of these regions; rather, the mechanism for which the greatest z-score value was calculated varied by gauge. The lack of consistent behavior in Colorado Plateau and Basin and Range gauging stations imply that neither regions has a mechanism that uniformly produces peak flow events larger than those of other flood-producing mechanisms throughout the region. These results may also be a lack of reliable data for the Colorado Plateau and the Basin and Range Province, in both the number of gauging stations and the number of peak flow events throughout the study period that are available.

The results of Pearson's chi-square test of independence comparing the ranking of peak flow events within a watershed to the mechanism that produced them, performed for five Arizona watersheds, showed that in some watersheds the ranking of a peak flow was not independent of the mechanism that produced it. However, in some other watersheds the ranking of peak flows were independent of mechanism. The peak flows were ranked in two different ways: by the raw discharge of the event, and by the z-score relative to the station at which it was observed. Ranking of peak flows in the Gila and Verde watersheds were found to not be independent of the mechanism that had produced it, regardless of how the peaks had been ranked – there was some level of dependence on the mechanism that had produced the flood and how large it had been compared to other peak flows in the watershed. In the Santa Cruz watershed, ranking was independent of the mechanism that had produced the peak flow regardless of how the peaks were ranked. For the Salt and the Little Colorado, however, the significance of the results varied with the method of ranking. Peak flows in the Little Colorado watershed were found to not be independent of the flood-producing mechanism only when the peaks were ranked by z-score, while in the Salt watershed the ranking was not independent of the flooding mechanism when the peaks were ranked by discharge. These results show that not all watersheds are affected by flood-producing mechanisms in the same way – that in one watershed a specific flood-producing mechanism may be responsible for most of the largest peak flow events seen in that watershed, but for another watershed the flooding mechanism may have little to no effect on how large a peak flow event may be.

Comparing the difference in means of AR-related peak flows to non-AR related peak flows support the above results. Stations #18, 21, and 24 show a difference in the means of AR-related peak flows vs. the non-AR winter synoptic and summer convective peak flows. For these three stations, which are located in the Central Highlands in either the Salt or the Verde watersheds, the AR peak flows were found to be greater than non-AR peaks. Stations #1 and 5 in the Colorado Plateau and Station #32 in the Basin and Range Province showed the difference in means of AR peaks and non-AR peaks were not statistically significant at these three stations, and concluded that there was not enough evidence to say that AR peaks are larger than non-AR peaks. The remaining stations, #6, 8, 11, and 27, are in Central Highlands watersheds that are not the Salt or the Verde. The results of these stations showed that AR-related peak flows were larger than peak flows of one non-AR flood producing mechanism, but the difference in means of the other non-AR mechanism were not statistically significant.

From these results it can be concluded that for some regions and watersheds, ARs produce flooding events of greater magnitude than other flood-producing mechanisms. But ARs are not a universal producer of large flooding events throughout Arizona, and their influence appears mostly limited to specific watersheds in the Central Highlands.

3. *What variables, if any, appear to affect the frequency, magnitude, and location of AR-related flooding?*

The location of AR-related flooding was determined to be limited primarily to the Central Highlands region, and within this region mostly in the Salt and Verde watersheds. This may be partly due to the terrain of the Central Highlands and the orography of this region, as orographic features can be a very strong influence in the location of AR-related flooding (Smith et al. 2010).

A comparison of seven basin characteristic variables to the AR fraction values at gauging stations throughout Arizona showed that there were no universal variables that were in relation to the AR fraction. Not one variable was found to affect all three regions simultaneously and in the same manner. However, each variable had some relationship to the AR fraction of at least one region.

There appears to be no universal variable or variables that affect AR-related flood events. Of the seven basin characteristic variables that had been compared to AR fraction, only outlet elevation affected all three physiological regions, decreasing in AR fraction as the elevation increased. Each basin characteristic had some degree of relationship to AR fraction of at least one region. AR fractions for the Central Highlands stations appeared to have some relation with soil permeability and forest cover. The drainage basin area, maximum elevation, and soil permeability were variables that seemed to affect the AR fraction of Colorado Plateau stations. Maximum elevation, percentage of slope greater than 30°, the mean basin slope, and the percentage of forest cover were variables that may influence AR fractions in the Basin and Range Province. This suggests that there are different factors that affect different watersheds and regions to varying degrees, and that a combination of various characteristics are likely in play in AR-related flooding.

One variable that may affect whether an AR event will produce flooding or not is the general trajectory and direction at which the AR had intersected the North American coastline. ARs that maintained a northwestern or northerly trajectory upon intersecting the coastline produced flooding events more often than ARs that had a westerly trajectory upon intersecting the coast. In addition to this, ARs that penetrated the interior through the Baja Peninsula coast were more likely to produce flooding than those that had made landfall through the Southern California coastline. These observations are in agreement with Rutz and Steenburgh (2015), which stated that there were certain trajectories and paths of entry (the Baja Peninsula coast being one of them) that are favorable for inland penetration of ARs.

6.1 Case Studies

This section will discuss two AR-related flooding events in detail: the 21 February 1996 AR event and the 5 January 2008 AR event. These two events were selected based on the characteristics of the AR that produced flooding or if the flood event itself was unusual.

6.5.1 21 February 1996

The AR on 21 February 1996 originated in the tropics near Hawaii. It has a northeast orientation and intersects North America at the southern border of California and the northern border of Baja California in the SSM/I (Figure 15). This AR can be seen in the SSM/I as early as February 19 UTC AM and persisted until February 22 UTC AM. This event produced a single annual peak at the gauging station at PAR-Lee, located in the Upper Colorado watershed in the Colorado Plateau. Despite the persistence of this AR event and the presence of IVT measured overhead other stations throughout Arizona, no peaks at any other gauging stations were observed.

This lack of AR-related flooding activity despite the presence of a persistent AR that intersected North America at a favorable trajectory and region shows that not all flood-producing ARs are large-scale events. An AR event with large IWV or IVT content that was detected throughout Arizona will not necessarily produce widespread flooding, or even extreme flooding, in Arizona watersheds.

6.5.2 5 January 2008

The AR event on 5 January 2008 produced flooding in the Transition Zone watersheds, at Station #6 in BSN-Wku in the Big Sandy watershed, and at Station #2 in the Paria River of the Upper Colorado watershed. An AR with a northeastern trajectory was observed to be intersecting the North American boundary on the 5 January UTC AM and PM passes, but had dissipated by the next pass (Figure 16). It originated in the tropics near Hawaii and made landfall at the border of Southern California and Baja California.

Twenty gauging stations in this study observed peak flows associated with this event, but only three of these peaks were annual peaks. This AR event was observed throughout all stations in Arizona, even if it did not produce flooding in most Colorado Plateau stations and the southeastern Basin and Range.

This event was less persistent than the AR event that occurred on 21 February 1996, but produced more flood peak events. The trajectory and the locations at which the two AR events are shown to be making landfall in the SSM/I are also very similar, so these are not likely to be a factor in the differences in flooding behavior of the two events. This suggests there may be other variables that influence the likelihood or the magnitude of flooding activity in watersheds.

Most of the gauging stations that flooded in response to this event were in the Transition Zone, which supports earlier findings in this study that the Transition Zone is the most AR sensitive region of Arizona. With the exception of the stations at PAR-Lee and BSN-Wku, there was no AR activity in the Little Colorado or Basin and Range regions for this event.

7. Conclusions

The role of atmospheric rivers as Arizona flood producers and how they compare to other Arizona flood-producing mechanisms were investigated in this study. The results showed that ARs play an important part in flooding in Arizona watersheds, but that their importance and effects are not widespread throughout the state and are more regionalized in specific parts of the state. Previous studies of Arizona ARs have focused primarily on the characteristics of a specific AR event (Neiman et al. 2013), the AR activity within a specific region of Arizona (Rivera et al. 2014), or the general behavior of ARs that may affect Arizona (Rutz et al. 2015). This study provides an insight into the trends seen in the AR activity and behavior throughout the state of Arizona as a whole, and how ARs as a flood producing mechanism compare to the other flooding mechanisms that are present in Arizona.

The main findings of this study are:

1) Not all atmospheric river events produce flooding in Arizona, but AR events had been observed every year during the period of study.
2) ARs dominate the flood record of the Central Highlands, and most AR activity occurs in this region. Different watersheds within the Central Highlands also vary in AR sensitivity, with the Verde and the Salt watersheds observing the most AR-related flooding events. In contrast, the Colorado Plateau and the Basin and Range Province observe very little AR activity.
3) Although ARs play a role in Arizona flooding, their importance is not universal. Unlike AR events that affect California and the other western Pacific Coast states, Arizona AR events do not necessarily produce the largest floods. Only in certain

regions of the Central Highlands were AR events likely to be responsible for the largest flooding events.

4) One of the most important variables as to whether an AR will produce flooding or not appears to be the trajectory at which the AR intersects the North American coast. ARs that made landfall at a northwestern or northerly trajectory were more likely to produce flooding than ARs that made landfall at a westerly trajectory. In addition to this, an AR that made landfall through the Baja Peninsula was likelier to produce flooding than an AR that intersected the Southern California coastline.

Future studies could be done on the variables that affect which AR events produce flooding and which events do not. Future research could study deeper the AR activity in the Colorado Plateau and the Basin and Range Province using additional stations and an expanded study period. By studying the flooding behavior of AR events in Arizona and how they compare to other flood-producing mechanisms, this study provides insight into the AR-related flooding risks that ARs present for different regions of Arizona and what factors may be influencing the flooding.

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Table 1. Research Design for Assessing the Role of Atmospheric Rivers as Flood Producers in Arizona

OBJECTIVE	PROCEDURE
(1) Identify Arizona flood peaks associated with Atmospheric Rivers (ARs) *(see Section 3)*	Select representative Arizona gauging station flood peak records to be assessed: • Annual peaks • Peaks-above base (partial duration series)
	Compile AR records for comparison with Arizona flood peaks based on a cross-referencing of data from multiple sources: • Compilations of ARs in published research • SSM/I satellite-based images of Integrated Water Vapor (IWV) • Gridded Integrated Water Vapor Transport (IVT) dataset
	Define criteria for: • AR-Associated Flood Peaks • AR Flood Days
	Compile master list of Arizona ARs : • ARs associated with floods • ARs not associated with floods
	Compile Arizona AR image gallery: • Snapshots of SSM/I AR water vapor imagery
(2) Assess differences in AR peaks vs. non-AR peaks *(see Section 4)*	Comparison of: • Numbers of AR flood peaks vs non-AR peaks • Magnitudes of AR flood peaks vs Non- AR peaks
(3) Analyze spatial variability of AR flood influence in Arizona *(see Section 5)*	Compile AR Flood Map gallery: • Map spatial distribution of stations and watersheds flooding on each AR Flood Day • Compare with Arizona AR image gallery
	Investigate factors associated with spatial variability • Flood hydroclimatology • Physiographic regions • Other basin characteristics

Table 2. Site information for selected gauging stations shown on Figure 3

Map #	USGS Site #	Site Name	Project Code	Drainage Area		AR Fraction *	
				(mi^2)	(km^2)	Annual peaks only	All Peaks above base
Colorado Plateau Stations							
1	9379200	Chinle Creek nr Mexican Water	CHN-Nmw	3611.8		0.083	0.112
2	9382000	Paria R at Lees Ferry	PAR-Lee	1362.1		0.167	0.122
3	9384000	Little Colorado nr St. Johns	LCO-Stj	711.1		0.042	0.056
4	9401260	Moenkopi Wash at Moenkopi	MKW-Mnk	1.8		0.083	0.087
5	9402000	Little Colorado nr Cameron	LCO-Cam	23491.7		0.083	0.162
Central Highlands Transition Zone Stations							
6	9424450	Big Sandy nr Wikieup +	BSN-Wku	2562.3		0.458	0.464
7	9432000	Gila blw Blue Ck, nr Virden NM	GIL-Blu	1988.2		0.292	0.257
8	9444500	San Francisco at Clifton	SFR-Clf	2764.9		0.375	0.436
9	9447000	Eagle Ck nr Morenci	EAG-Mor	621		0.375	0.407
10	9447800	Bonita Ck nr Morenci	BON-Mor	302.3		0.292	0.306
11	9448500	Gila nr Solomon	GIL-Sol	0.77		0.375	0.377
12	9466500	Gila at Calva	GIL-Cal	11543.2		0.375	0.339
13	9468500	San Carlos nr Peridot	SCL-Per	1025.8		0.458	0.442
14	9490500	Black nr Fort Apache	BLK-Fta	1223.7		0.458	0.525
15	9492400	East Fork White nr Fort Apache	EFK-Fta	21.7		0.333	0.333
16	9497800	Cibecue Ck nr Chrysotile	CIB-Chr	290		0.292	0.309
17	9497980	Cherry Ck nr Globe	CHE-Glo	199.8		0.417	0.56
18	9498500	Salt nr Roosevelt	SLT-Roo	4289.4		0.542	0.485
19	9499000	Tonto Ck nr Roosevelt	TON-Roo	672.2		0.458	0.57
20	9504000	Verde nr Clarkdale	VRD-Crk	3507.2		0.458	0.52
21	9504500	Oak Ck nr Cornville	OAK-Crn	355.1		0.458	0.54
22	9505350	Dry Beaver Ck nr Rimrock	DBV-Rim	142.1		0.417	0.47
23	9505800	West Clear Ck nr Camp Verde	WCL-Cmp	241.4		0.542	0.5
24	9508500	Verde abv Horseshoe Dam	VRD-Hsd	5870		0.542	0.5
25	9510200	Sycamore Ck nr Fort Mcdowell	SYC-Mcd	164		0.458	0.493
26	9512500	Agua Fria nr Mayer	AFR-May	585.2		0.292	0.319
27	9513780	New nr Rock Springs	NEW-Rck	68.4		0.5	0.466
Basin and Range Stations							
28	9470500	San Pedro at Palominas	SPD-Pal	738.3		0.083	0.065
29	9471000	San Pedro nr Charleston	SPD-Cha	1216.2		0.083	0.121
30	9473000	Aravaipa Ck nr Mammoth	ARV-Mth	537.6		0.167	0.286
31	9480000	Santa Cruz nr Lochiel	SCR-Loc	82		0.042	0.03
32	9480500	Santa Cruz nr Nogales	SCR-Nog	531.7		0.125	0.156
33	9486000	Santa Cruz at Tucson	SCR-Tuc	2191.9		0.042	0.075

* AR fraction for each station = (total AR peaks / total observed peaks) see Section 4

+ The Big Sandy watershed heads in the far western area of the Central Highlands Transition Zone and has Basin and Range characteristics in its lower reaches .

Table 3. Definitions of atmospheric rivers from various sources in chronological order.

AR Definition	Reference
"characterized by strong gradients in a southwest flow of moist stable air from a rather distant low-latitude source, with a minimum of interruption by intrusion of air from a more northerly source"	Weaver 1962 (p. 207)
"water vapor transport in the troposphere is characterized by a filamentary structure"; "the fraction of the globe they cover is 10% or less"	Zhu and Newell 1998, based on Newell and Zhu 1992
"quite narrow (<1000 km wide) relative to both their length scale (>~2000 km) and to the width scale of the sensible component of heat transport"	Neiman et al. 2008a
[Pineapple express] "steer warm, moist air from the tropics near Hawaii northeastward into California"	Dettinger 2011, based on Weaver 1962; Dettinger 2004
"as they approach the west coast of North America, ARs are typically 2,000 or more kilometers long but only a few hundred kilometers wide"	Dettinger 2011, based on Ralph et al. 2006
"areas of strong winds (greater than 12.5 ms^{-1} wind speed […]) with an Integrated Water Vapour (IWV) in the atmospheric column of more than 2 cm"	Lavers et al. 2011, based on Ralph and Dettinger 2011 and Ralph et al. 2004
"concentrate those fluxes into long (>~2000 km), narrow (<~1000 km) plumes"	Neiman et al. 2011, based on Bao et al. 2006; Stohl et al. 2008; Ralph et al. 2011
"narrow plumes of SSM/I vapor with values >2 cm that were >2,000 km long and <1,000 km wide"	Dettinger et al. 2011
"thousands of kilometers long and, on average, only 400 km wide"	Ralph and Dettinger 2012
"a contiguous region ≥2000 km in length and ≤1000 km in width containing IWV values ≥20 mm"	Rutz and Steenburgh 2012
"long (>2000 km), narrow (<1000 km), low-level (below ~600 hPa) plumes of enhanced water vapor flux"	Neiman et al. 2013, based on Zhu and Newell 1998; Ralph et al. 2004, 2005, 2011; Neiman et al. 2008a, b; Smith et al. 2010
"long (about 2000 km), narrow (about 300-500 km wide) bands of enhanced water vapor flux"	Gimeno et al. 2014 (p.1), based on Newell et al. 1992
A plume of water vapor >2000 km long, <1000 km wide, and IWV value of >2 cm.	This study, based on Dettinger et al. 2011 and Rutz and Steenburgh 2012

Table 4. Arizona flood-related atmospheric river dates by month (WY 1988 – 2011)

WY^{+}	**Seasonality of AR Flood Events during each Cool-Season Month** *numbers in each column below indicate the date, e.g., Oct 31, Jan 17*								**Annual Totals**		
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	Total AR-flood days	Total AR non-flood days	Total AR-Days
1988	31			17			20*, 28*		4	N/A	4
1989	14*			4		7, 11			4	7	11
1990									0	4	4
1991				4		1, 5, 26	6*, 10*		6	5	11
1992				5	13	5	13*		4	1	5
1993			5, 28	6, 16	7, 19, 24*, 26*	17			9	1	10
1994		22			7	20			3	3	6
1995			6	4, 12, 25	14	4, 10			7	3	10
1996					21				1	6	7
1997				3, 25					2	3	5
1998	2				8, 14, 17, 23	25, 28			7	3	10
1999	25*								1	6	7
2000									0	3	3
2001	10, 29*	6			13			1	5	2	7
2002			14*						1	6	7
2003		9			13, 25	15	14		5	1	6
2004		12							1	2	3
2005	20, 27		28	4, 10	11, 15, 19, 21	19*			10	2	12
2006									0	7	7
2007				5*					1	2	3
2008		30	7	5, 27	4, 22	29*			7	0	7
2009			17, 25		16, 23	3			5	2	7
2010				20, 22	6*	20*			4	4	8
2011			21, 29		19	2*			4	2	6
Total	**8**	**5**	**10**	**18**	**25**	**18**	**6**	**1**	**91**	**75**	**166**

* indicates that an AR was observed in SSM/I imagery only on this date

\+ indicates El Niño WYs: . strong: **1998** , moderate: 2003 , weak: 2005 source: ggweather.com/enso/oni.htm

Table 5. Contingency table for evaluating the importance of AR vs. non AR mechanisms on Flood Peak Rank. Shown are the number of events in each category
Stations # 7, 11, and 12 the Gila River below Blue Creek near Virden, the Gila River near Solomon, and the Gila River at Calva

	AR-Related	**Non-AR Winter**	**Convective**	**Tropical**	**Total**
Top Third	17	15	4	0	36
Medium Third	5	18	9	3	35
Bottom Third	6	8	19	2	36
Total	28	42	32	5	107

Table 6. Chi Square Test results for the selected watersheds (based on actual discharge)

Station	**χ^2 (Discharge)**	**χ^2 (z-score)**
#7, 11-12 Gila	26.1*	17.63*
#20, 24 Verde	23.4*	30.24*
#31-33 Santa Cruz	1.97	3.58
#3, 5 Little Colorado	9.87	18.15*
#18 Salt	19.15*	16.15

** indicates significance (at the .01 level with six degrees of freedom, the chi-square test statistic must exceed 16.81 to be significant)*

Table 7: The t-statistic values for difference in means of AR and non-AR peaks

Station	**AR vs. Non-AR Winter**	**AR vs. Convective**
#6 Big Sandy nr Wikieup	3.447*	2.356
#1 CHN-Nmw	-0.411	0.058
#11 GIL-Sol	1.77	3.918*
#5 LCO-Cam	2.156	1.101
#27 NEW-Rck	3.361*	1.91
#21 OAK-Crn	5.25*	3.766*
#32 SCR-Nog	1.624	1.813
#8 SFR-Clf	1.756	3.613*
#18 SLT-Roo	3.362*	3.22*
#24 VRD-Hsd	5.692*	4.09*
** indicates significance at the .01 level; see Appendix D for individual results*		