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

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

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Map #** | **USGS Site #** | **Site Name** | **ProjectCode** | **Drainage Area**  | **AR Fraction \*** |
| (mi2) | (km2) | Annual peaksonly | All Peaksabove 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](http://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** | **χ2 (Discharge)** | **χ2 (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* |