**Characterizing High Intensity Precipitation Within Landfalling Atmospheric Rivers Along the West Coast of the United States**

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# Introduction

High intensity precipitation events are described by their unusually high rates of precipitation over a given duration of time, However, these events can also be distinguished by the various impacts that result from them. As known drivers of rapid and potentially hazardous changes in landscape through flash flooding, erosion, snow melting, landslides, and debris flows (IPCC, 2022), extreme high intensity precipitation (HIP) events can lead to high socioeconomic costs through their ability to simultaneously affect drinking water supplies, fishery health, and transportation infrastructure over short time periods. As studies have suggested that these kinds of precipitation events are likely to increase in intensity as the climate warms (Kunkel et al., 2013), understanding the physical characteristics of synoptic and meso-scale HIP events is critical for the development of future mitigation strategies and infrastructure improvements.

Previous research has investigated spatial and temporal patterns of high intensity precipitation along the West Coast of the US. For example, Ralph et al. (2006) and Neiman et al. (2011) used radar and streamflow data to analyze and document extreme precipitation events in California’s Russian River and Washington’s Olympic and Cascade Mountains. Guan et al. (2010) similarly analyzed precipitation data from the Sierra Nevada Mountain Range in California and found that the largest precipitation events were associated with atmospheric rivers (ARs), synoptic-scale (1000 km or larger) narrow bands of water vapor that can transport large amounts of moisture out of the tropics to the mid-latitudes. Atmospheric rivers account for a significant proportion of high impact hydrological events in California (Young et al. 2017).

Within these large-scale systems, smaller mesoscale characterizations of HIP events have also been described. Because of California’s unique water resource dependencies on a few extreme precipitation events during the winter season, numerous studies have utilized the state’s topographic variability and large spatial extent to describe HIP events in relation to orographic drivers and AR storm-level summary analyses (Lamjiri et al. (2018); Cannon et al. (2017)). Additional work has been done to describe smaller scale meteorological features embedded within ARs that contribute to HIP events. Convective narrow cold frontal rainbands (NCFRs) are a characteristic of particularly sharp frontal boundaries and are often accompanied by strong gusty winds and brief but intense precipitation. Studies have shown that the “precipitation cores” formed within NCFRs are associated with high surface convergence and some of the highest rates of precipitation in storms where the phenomena is observed (Houze et al., 1976; Hobbs & Persson, 1982; Koch & Kocin, 1991). These systems have additionally been associated with many costly and destructive debris flow and landslide events in Southern California (Cannon et al., 2018; Oakley et al., 2017; Sukup et al., 2016, de Orla-Barile, 2022).

Notable events illustrate the socioeconomic impact of HIP. In 2017, the Oroville Dam Crisis in the state of California was in part triggered by a series of atmospheric river events that affected the region in early February. The pulses of high intensity precipitation within these AR events caused heavy damage to the primary and emergency spillway of the Oroville Dam, leading to the evacuation of 188,000 people and around $1 billion in damage-related repairs (Henn et al., 2020; Vano et al., 2018; White et al., 2019). As the hydroclimate of California is dominated by wild swings in drought and non-drought years, similar annual extreme events within the state often impact the hydrologic and geomorphic response to precipitation by changing the physical relationships among rainfall, runoff, erosion, and hillslope stability. HIP events that trigger these landscape responses increase the risk of multiple disasters where water and emergency managers face increasingly dire tradeoffs between water quality, transportation networks, community safety and flood prevention. Recent studies (Agilan, et al., 2017; Chanaud et al., 2021) have found that precipitation intensity-duration-frequency (IDF) relationships have changed from the historical curve in many regions, with many of these changes found in higher intensity, shorter duration events. Because these curves are oftentimes used to design water control infrastructure, and the design of long-lifetime infrastructure is that the curves represent a stationary climate, non-stationarity implies risk to infrastructure and socioeconomic health.

Previous scholarly research has identified two distinct challenges associated with the current state of high intensity precipitation research:

1. **Poor understanding of processes that cause high intensity precipitation.**

It is known that the highest precipitation rates on earth are found in deep convective cells. However, the details of how convective elements organize or how strong rising motion embeds within larger precipitating systems (e.g. cyclones or fronts) are poorly understood and are critical for understanding how high rates persist long enough to cause significant impact.

1. **Poor understanding of the landscape responses to high intensity precipitation.**

Rainfall intensity is known to affect land surface processes such as infiltration, runoff efficiency, erosion, and runoff/liquid water retention during rain-on-snow events and sensitivity to HIP has been well-studied via laboratory and computational experiments. However, landscape scale processes are less understood (I.E. flash flooding, debris flow and landslide initiation, mass erosion, stream network sediment loading, and snowpack loss) and may become exacerbated when events occur within disturbed regimes. Sequencing of intra-event HIP is known to modulate the above impacts, but little work has been performed to link the sequencing of HIP in real events to hydrological and geomorphic outcomes (Dunkerley et al., 2021).

# Study Objectives

Developing an understanding of the mesoscale features of HIP events will address the above challenges by improving the ability to accurately project these events in future climates through dynamical and statistical means, highlighting critical uncertainty in detection and prediction, providing gains in predictive skill and scientific insight into the impact of HIP on changing landscapes, and generating new decision-support information to assist water and environmental resource managers in developing the next generation of adaptive management practices.

This case study will provide mesoscale characterizations for a series of landfalling ARs that triggered the February 2017 Oroville Dam Crisis in the state of California. Rain gauge, satellite-based, and reanalysis data will be used to identify high intensity, short duration precipitation pulses embedded within these ARs, and the local and synoptic-scale forcing characteristics attributed to these pulses will be identified and statistically described. Results will provide insight into how short duration high intensity precipitation propagates within larger storm systems and will expand our understanding of the mechanisms that drive high intensity precipitation variability from within-storm events.

# Data and Methods

## Study Region

This work is associated with the Forecast-Informed Reservoir Operations (FIRO) project from Scripps Center for Western Weather and Water Extremes Forecast Informed Reservoir Operations. The project is designed to utilize forecasting capabilities to inform and enhance water management within reservoir operations in the state of California. The Yuba-Feather watershed region consists of river systems that have a long history of catastrophic flooding, with five major floods resulting in 41 deaths since 1950 (FIRO). The region was identified as one of interest because of this climatological propensity to be affected by extreme precipitation events that often lead to high socioeconomic impacts.

A map of california with a red and yellow location

Description automatically generated

Figure 1. Study watershed region of interest

## MesoWest Station Data

This study utilizes rain gauge data to approximate precipitation within the Yuba-Feather watershed region. The University of Utah’s MesoWest project provides access to archived weather observations across the United States, with extensive records of hourly precipitation available for many airport-based stations across the country. The station located at the Oroville Municipal Airport has an extensive record of hourly precipitation data and was used to pull hourly precipitation records for February 2017. Raw precipitation data from MesoWest required resampling to consolidate precipitation values to the nearest hour. Data with multiple time stamps per hour were resampled using the mean value across each respective hour.

|  |  |  |  |
| --- | --- | --- | --- |
| **Watershed Region Name** | **Station Name** | **Station Code** | **Years of Data Available** |
| Yuba-Feather | Oroville | kove | 24 |

Table 1. MesoWest sites selected for analysis

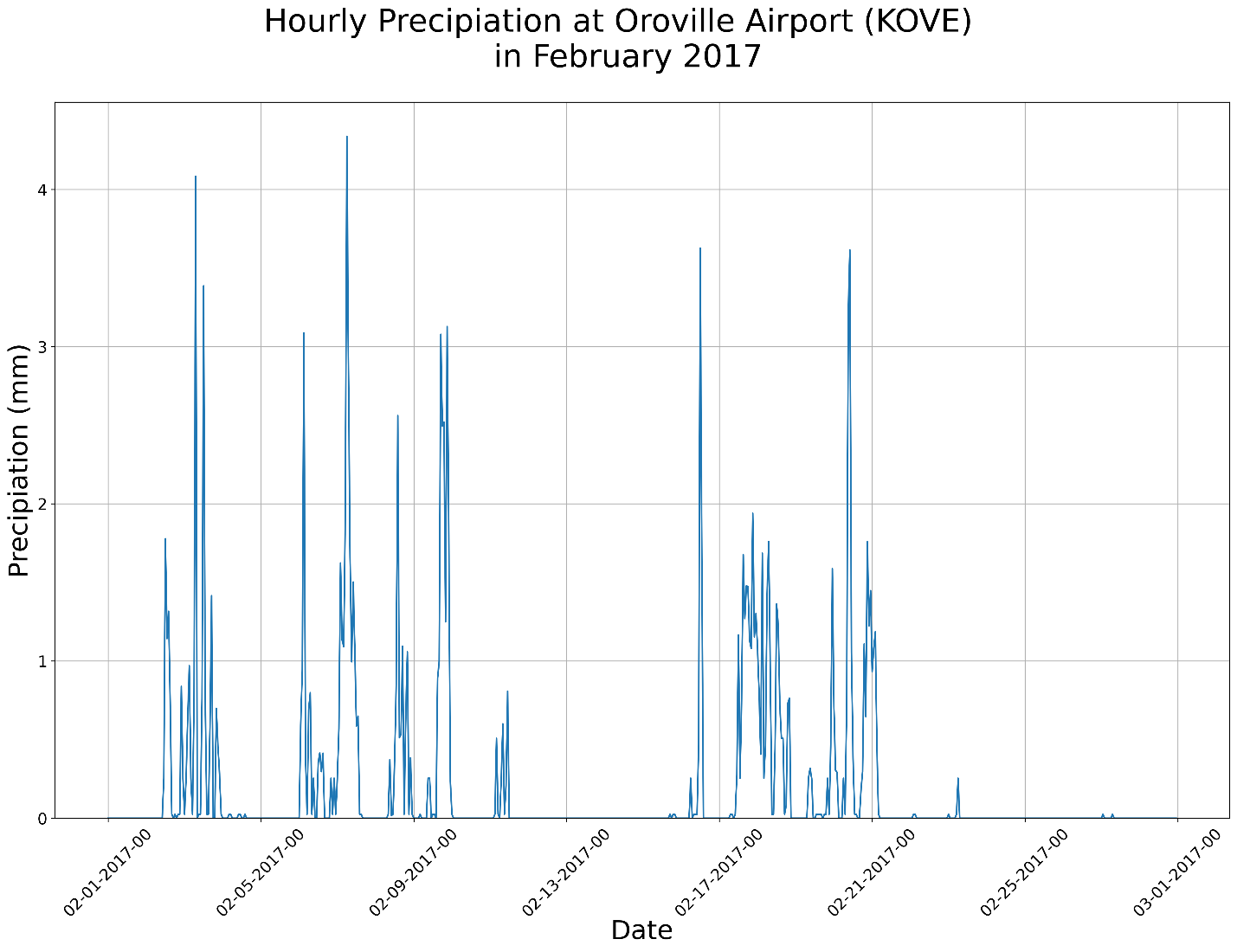


Figure 1. Resampled precipitation time series for Oroville Airport, California (Yuba-Feather watershed)

## Pulse Case Identification

Pulses of precipitation were identified by isolating precipitation totals that were at or above the 95th percentile of total events for the entire period of record for each station. These events are further filtered to capture scenarios that contain multiple distinct pulses in rainfall intensity. These multimodal events were determined by finding hourly episodes of rainfall separated by at least 12 (TBD) days of zero hourly precipitation. For this case study, single short and long-term multimodal events are identified, with short-term events representing a total temporal range of 2-3 days and long-term events representing 3 or more days.

A graph of different types of data

Description automatically generated with medium confidence

Figure 2. Example of “multimodal” pulses found within AR at Oroville Airport in February 2017

## Characterizing Multimodal Events

Events identified by the methodology above will be evaluated and described through both synoptic-scale and meso-scale products:

### MERRA II Reanalysis

Synoptic-scale characterizations of the identified HIP will be utilized to describe the large-scale patterns influencing these precipitation pulses. Reanalysis data from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) will be used as a diagnostic tool to describe the flow of moisture into the Yuba-Feather watershed region. The direction and magnitude of this high-level moisture profile will provide information on which locations within the region are more affected by pulses of high intensity rainfall. Because the directionality and intensity of moisture is the primary driver, MERRA-II”s integrated water vapor transport will be the primary product used for this synoptic-scale characterization effort.

A map of the weather

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Figure 3. Example of IVT for February 7th at 07:00 UTC

### Multi-Radar Multi-Sensor Quantitative Precipitation Estimation:

The Multi-Radar Multi-Sensor (MRMS) system designed by NOAA/National Severe Storms Laboratory (NSSL) integrates over 180 operational US WSR-88D weather radars, hourly gauge observations, and model analyses to create gridded precipitation products (Zhang et al., 2016). Quality-controlled radar reflectivity data is interpolated onto a 3D grid, with precipitation type (e.g. stratiform, convective, and snow) and surface rates derived at each grid point every 2 min. Hourly MRMS quantitative precipitation estimate (QPE) products with 1-km resolution will be linked to precipitation pulses identified as exhibiting suspected HIP activity. As a derived measurement of accumulated precipitation, QPE products will be utilized to build a comprehensive picture of total rainfall spatial variability for each individual pulse of precipitation within the February 2017 storm systems.

A map of the united states

Description automatically generated

Figure 4. Example of QPE for February 7th at 7:00 UTC

### NEXRAD Doppler Radar

The Next Generation Weather Radar (NEXRAD) is a network of 160 high-resolution Doppler radar sites that detects precipitation and atmospheric movement and disseminates data in approximately 5-minute intervals from each site. NEXRAD enables severe storm prediction and is used by researchers and commercial enterprises to study and address the impact of weather across multiple sectors. The NEXRAD radar located at Beale Airforce Base in Yuba City, California will be used to identify sub-hourly mesoscale features associated with each precipitation pulses within the watershed region. High intensity, short duration extreme rainfall events often occur at this temporal resolution, making the 5-minute intervals of the NEXRAD network imperative for this analysis.

A map of a storm

Description automatically generated

Figure 2. NEXRAD Reflectivity at Beale Airforce Base on February 7th, 2017

# Preliminary Results:

Pulses flagged as having HIP will be characterized in a catalog that will include general physical characteristics of the event (timing, location of watershed/station, etc), any associations with NCFRs or ARs, and any known landscape/infrastructure impacts. Additional features of selected HIP events (notable storm structures, particularly defined NCFRs, etc) will be highlighted in this section.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Start  Date/Time** | **End  Date/Time** | **NCFR** | **AR/**  **AR\_CATEGORY** | **Any Known**  **Impacts on Landscape/**  **Infrastructure** |
| 01/5/2016 H:15 | 01/7/2016 H:15 | Yes | Yes/5 | No |

Table 2. Example Catalog Entry (note: test data)

# Discussion and Broader Implications

The development of a catalog describing these characteristics has benefits for a wide variety of academic and non-academic communities.

The Center for Western Weather and Water Extremes Forecast Informed Reservoir Operations will be able to use these results to help develop more informed strategies for efficiently managing reservoir levels throughout California. As high intensity precipitation is not well understood in numerical models and poorly represented in longer-term climate data (Stephens et al., 2019, Martin et al., 2018, Suzuki et al., 2015, Dunkerley et al., 2010), the statistical characterizations from this study will also provide beneficial research for improving weather and climate forecasts in general. The public will also see benefits from the research proposed as understanding the local mechanisms underlying these extreme events will allow for the improvement of warning systems in vulnerable communities and can assist in the development of preemptive mitigation strategies to save property and lives.

There are opportunities for future research with this proposed project. All data being used is available for the full spatial extent of the United States, so an expansion of this catalog to more locations can be implemented with relative ease. Additional meteorological variables can also be easily incorporated into the catalog to provide a fuller picture of the mesoscale environments in which these high intensity precipitation events develop.

Below is a proposed timeline for the project, based on credits needed and deliverables expected:

|  |  |  |  |
| --- | --- | --- | --- |
| **MS in Geography  objective timeline** | **Fall 2024 (Defend Thesis Proposal)** | **Winter 2024** | **Spring 2024 or Fall 2025  (Defend Thesis)** |
| **Action Items** | Defend Thesis Proposal | Continue research/Masters Thesis | Defend Thesis |

Table 3. Proposed research timeline

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