THE RELATIONSHIP BETWEEN INTEGRATED WATER VAPOR TRANSPORT AND CALIFORNIA WATERSHED PRECIPITATION

by

Joseph Anthony Ricciotti
B.S. Plymouth State University, 2019

THESIS

Submitted to Plymouth State University
in Partial Fulfillment of
the requirements for the Degree of

Master of Science
in
Applied Meteorology

May 2021
This thesis has been examined and approved.

Thesis Advisor, Dr. Jason M. Cordeira
Associate Professor of Meteorology
Meteorology and Physics Program
Plymouth State University

Dr. Eric G. Hoffman
Professor of Meteorology
Meteorology and Physics Program
Plymouth State University

Chad W. Hecht
Meteorology Staff Researcher
Center for Western Weather and Water Extremes
Scripps Institution of Oceanography at UC San Diego

5/4/2021
Date
ACKNOWLEDGEMENTS

This thesis would not have been possible without funding from the State of California, Department of Water Resources (#4600013361) and the U.S. Army Corps of Engineers (W912HZ-15-2-0019, W912HZ-19-2-0023) as part of broader projects led by the Center for Western Weather and Water Extremes (CW3E) at the University of California, San Diego Scripps Institution of Oceanography.

Procurement and application of this funding towards my thesis was made possible by my thesis advisor, Dr. Jason Cordeira, for whom I am immensely thankful. His guidance, insight, and constructive criticism made this thesis possible, and I am incredibly grateful for his time and effort over my last few years at Plymouth State University.

I would also like to thank Dr. Eric Hoffman for being my undergraduate advisor as well as a member of my thesis committee. His unwavering patience and guidance through classes and research was exceptionally valuable. Also, I would like to acknowledge Chad Hecht as a member of my thesis committee. His excellent feedback defined and motivated this research through his knowledge into potential future application.

I would like to also acknowledge the rest of the faculty and staff at Plymouth State University. Thank you for making my undergraduate and graduate education meaningful and enjoyable. I will always have a strong appreciation for the experience you all created for myself and other meteorology students.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ iii

TABLE OF CONTENTS ........................................................................................................ iv

LIST OF TABLES ................................................................................................................... v

LIST OF FIGURES ................................................................................................................. vi

ABSTRACT ........................................................................................................................... viii

PREFACE ................................................................................................................................ 10

CHAPTER 1 ............................................................................................................................ 12

1. Introduction ....................................................................................................................... 12

CHAPTER 2 ............................................................................................................................ 16

2. Data & Methods ................................................................................................................ 16

CHAPTER 3 ............................................................................................................................ 21

3. Results ............................................................................................................................... 21

   a. Watershed MAP climatology ...................................................................................... 21

   b. Relationships among ARs, coastal IVT, and watershed MAP .................................... 22

CHAPTER 4 ............................................................................................................................ 33

4. Concluding Discussion ..................................................................................................... 33

REFERENCES ....................................................................................................................... 41
LIST OF TABLES

Table 1. Summary of correlation ($r^2$) values between IVT, the projected IVT (IVTp), the 925-hPa water vapor flux (925F), the 850-hPa water vapor flux (850F), or the projected IVT during the cool season (IVTp-cool) with watershed MAP. 27

Table 2. Summary of results for the HUC8 watersheds containing 12 California Lakes/Reservoirs, listed from north to south. 39
LIST OF FIGURES

Figure 1. Map of California HUC8 watersheds (black lines) and topography (m; shaded) with coastal CFSR grid points (black circles) and the four focal watersheds (shaded; see legend) used and discussed in this study. The locations of the 12 Lakes/Reservoirs highlighted in Table 2 are denoted by triangles (see legend). Image created using QGIS 3.12 with topography and watershed boundaries obtained from the United States Geological Survey. ..................19

Figure 2. Correlation ($r^2$; shaded) values between daily projected IVT and watershed MAP for the North Fork Feather watershed as a function of coastal location (latitude) and IVT direction. The maximum $r^2$ value is marked by the black dot. ..........................................................20

Figure 3. California watershed MAP climatology of (a) average annual MAP (mm), (b) percent of average annual MAP attributed to extreme events (%), (c) the number of days to receive half the average annual MAP (days), and (d) percent of average annual MAP attributed to AR days (%). ........................................28

Figure 4. Annual summary of annual MAP (gray bars), annual MAP attributed to extremes (red bars; top 5% of rainy days), and percentage of annual MAP attributed to extremes (black line) for (a) the North Fork Feather watershed, (b) the Upper Yuba watershed, (c) the Russian watershed, and (d) the Santa Ana watershed for WY 1982–2019. ..................................................29

Figure 5. Annual summary of MAP anomaly (green and brown bars) and frequency of AR days (black line) for (a) the North Fork Feather River watershed, (b) the Upper Yuba River watershed, (c) the Russian River watershed, and (d) the Santa Ana River watershed for WY 1982–2019. The AR frequency derived from IVT data in (a–c) at 37.5°N, 122°W and in (d) at 32.5°N, 117.0°W. ........30

Figure 6. California watershed maximum correlation values ($r^2$) for (a) IVT magnitude and watershed MAP and (b) projected IVT and watershed MAP. The coastal latitudes and IVT directions corresponding to the maximum correlations in (b) for each watershed are shown in panels (c) and (d). .........................31

Figure 7. California watershed maximum correlation values ($r^2$) for (a) projected 850-hPa water vapor flux and watershed MAP and (b) projected 925-hPa water vapor flux and watershed MAP, for comparison with the projected IVT and watershed MAP in Fig. 6b. The differences between the projected water vapor flux correlation values and the projected IVT correlation values are shown in (c) and (d). .................................................................32

Figure 8. California watershed maximum correlation values ($r^2$) for projected IVT and watershed MAP in (a) the April to September warm season and (b) the October to March cool season, for comparison with the projected IVT and watershed
MAP in Fig. 6b. The IVT directions corresponding to the maximum correlations in (a) and (b) for each watershed are shown in panels (c) and (d). Note that the colors for IVT directions on panels (c) and (d) differ from those colors for IVT directions in Fig. 6d.
ABSTRACT

THE RELATIONSHIP BETWEEN INTEGRATED WATER VAPOR TRANSPORT AND CALIFORNIA WATERSHED PRECIPITATION

by
Joseph Anthony Ricciotti
Plymouth State University, May, 2021

Atmospheric Rivers (ARs) are defined as corridors of enhanced integrated water vapor transport (IVT) and produce large fractions of annual precipitation in regions with complex terrain along the western coastlines of mid-latitude continents (e.g., 30–50% along the U.S. West Coast in California). This study investigates this relationship among landfalling ARs, IVT, and watershed mean areal precipitation (MAP) for a 38-year period over California. On average, the daily average IVT magnitude at different coastal locations explains ~34% of the variance in annual watershed MAP across all 140 watersheds with large spatial variability across California. Further investigation of the IVT magnitude and direction at coastal locations illustrated that adding water vapor transport direction increases the explained variance in annual MAP to an average of 45%, with highest values (~65%) occurring in watersheds over North-Coastal California. Similar investigation of the lower-tropospheric water vapor flux vector at 850 hPa and 925 hPa revealed further increases in the explained variance in annual MAP to an average >50%. The results of this study (1) emphasize the importance of IVT direction and water vapor flux altitude to watershed MAP, (2) align well with previous studies for select locations that highlight the importance of upslope (i.e., lower tropospheric) water vapor flux during landfalling ARs and precipitation, and (3) motivate the development of AR-related
and watershed-centric forecast tools that incorporate IVT direction and water vapor flux altitude parameters in addition to IVT magnitude.
PREFACE

Management of California’s water resources need to consider various applications related to hydroelectric power, flood control, conservation, wildlife, recreation, and water supply. Management is also complicated by California’s Mediterranean climate with wet and dry seasons. Balancing the aforementioned uses to properly manage water supply and flood control through water release decisions is the purpose of the Water Control Manual (WCM) which is created within a year or two of a dam’s completion. With many of these dams being completed decades ago, meaningful updates of WCMs need to occur.

The initiative to update these WCMs by developing, demonstrating, and implementing tools and science that enable more effective management of reservoirs by leveraging improvements in weather and water forecasts is the goal of Forecast Informed Reservoir Operations (FIRO; https://cw3e.ucsd.edu/firo/). FIRO was first applied to Lake Mendocino (Russian River) by applying forecasting techniques to inform decisions regarding increasing water supply without reducing existing flood protection. Next, FIRO is producing a primary viability assessment for the Prado Dam in the Santa Ana River watershed in Southern California which aims to enhance water conservation through stormwater capture while improving flood risk management. The other two dams currently in the FIRO process are the New Bullards Bar and Oroville Dams which are also aiming to improve flood risk management without adversely affecting water supply in the Yuba and Feather River watersheds, respectively.
These four reservoirs and their watersheds are focal points in this thesis due to the aforementioned increased FIRO interest. The natural linkage between research and application that FIRO creates is prevalent within this thesis. Application of this thesis focuses on a potential to inform existing and new forecasting tools that may incorporate meteorological characteristics of landfalling atmospheric rivers, the storms responsible for a majority of California’s annual and extreme precipitation, to the forecast process. This thesis and future work derived from the results of this thesis aim to provide researchers, forecasters, and water resource managers additional information that can enhance situational awareness and improve the FIRO-related decision-making process.
CHAPTER 1

1. Introduction

Water resources in California are highly dependent upon spatial and temporal precipitation variability on daily, monthly and annual timescales (Dettinger et al. 2011). Precipitation events occur with a frequency of ~25–45 events per year in northern California and ~2–15 events per year in southern California (Dettinger et al. 2011; Lamjiri et al. 2018), and generate ~50% of the state’s annual precipitation on ~5–20 days (Dettinger et al. 2011). This regional variability also exists across individual watersheds where precipitation and its impacts from a single event may range from beneficial in one watershed to hazardous in a nearby watershed (e.g., Ralph et al. 2003; Neiman et al. 2011). The source of ~30–50% of this precipitation, its variability, and subsequent impacts to the hydrosphere is often attributed to the occurrence or non-occurrence of Pacific winter storms and their landfalling atmospheric rivers (ARs; e.g., Neiman et al. 2002, 2008b; Ralph et al. 2003, 2004, 2006; Dettinger et al. 2011, 2013; Ralph and Dettinger 2012). The goal of this study is to use a watershed-centric focus to (1) summarize the relationships among California’s precipitation extremes, annual precipitation, and landfalling ARs and (2) identify the physical characteristics of landfalling ARs that may best relate to variability in watershed-scale precipitation across the state.

ARs are long and narrow corridors of enhanced integrated water vapor (IWV) and integrated vapor transport (IVT) primarily driven by a pre-cold frontal low-level jet stream (LLJ) of an extratropical cyclone (AMS 2019). A majority of the IVT (~75%) in ARs is occurs in the lowest 2.25 km of the atmosphere (Ralph et al. 2006),
often leading to orographic precipitation along coastal and inland mountain ranges where ARs make landfall across the western U.S. (e.g., Ralph et al. 2004, 2005, 2017; Neiman et al. 2008a, 2011; Rutz et al. 2014, 2015). The orographic precipitation is maximized where lower-tropospheric water vapor flux within an AR is perpendicular to topographic barriers. Therefore, for a given water vapor flux magnitude and direction, spatial variability in topography (e.g., slope and aspect) may influence spatial variability in precipitation (e.g., Ralph et al. 2003, 2004, 2006; Neiman et al. 2011; Hughes et al. 2014; Hecht and Cordeira 2017). This spatial variability in observed precipitation may also contain similar spatial variability in associated hydrometeorological hazards depending upon local antecedent conditions such as soil moisture, wildfire activity, or upstream snowpack. For example, landfalling ARs are simultaneously implicated in drought amelioration (Dettinger 2013), reservoir and snowpack replenishment (Guan et al. 2010, 2012), floods and insured flood losses (Corrinking et al. 2019), and may contribute to post-fire debris flows and landslides (Oakley et al. 2017; Young et al. 2017; Cordeira et al. 2019), among other extremes.

In addition to variability in terrain slope and aspect, the spatial variability in observed precipitation may also be influenced by meteorological processes related to (1) variability in water vapor flux magnitude, direction, and elevation, (2) stability such as buoyant or slantwise convection along narrow cold frontal rain bands (e.g., Ralph et al. 2011; Cannon et al. 2020) or the presence of barrier jets (e.g., Kingsmill et al. 2013; Neiman et al. 2013b; Ralph et al. 2016), (3) precipitation processes such as the seeding of orographic precipitation from higher-altitude synoptic-scale driven precipitation (e.g., Bergeron 1965; Browning et al. 1974; Storebø 1976; Hill &
Browning 1979; Browning 1980; Hill 1983; Neiman et al. 2002; Ralph et al. 2003), or
(4) a reduction or enhancement in downstream orographic precipitation due to
shadowing from upstream topography or the presence of terrain gaps, respectively. For
example, orographic precipitation during landfalling ARs is typically reduced across
the inland Northern Sierra Nevada due to a decrease in water vapor transport from
shadowing by the Coastal Ranges. Alternatively, precipitation may be locally
enhanced when water vapor flux is directed through a terrain gap in the Coastal
Ranges such as near the San Francisco Bay or Petaluma areas (e.g., Neiman et al.
2002, 2013b; Rutz et al. 2014; White et al. 2015; Lamjiri et al. 2018). The presence of
the southerly Sierra barrier jet along the west slope of the northern Sierra Nevada
during a landfalling AR may also enhance precipitation across the northern Central
Valley and northeast California near Lake Shasta (e.g., Neiman et al. 2013b; Ralph et
al. 2016).

Across North-Coastal California, the storm-total bulk-upslope water vapor flux
associated with a landfalling AR is a parameter often related to variability in observed
storm-total precipitation (Ralph et al. 2013). The bulk-upslope water vapor flux is the
upslope component of lower-tropospheric water vapor flux that has been projected
onto the local terrain gradient vector and represents a portion of the IVT vector (i.e.,
the “projected IVT”) (Neiman et al. 2002, 2009). The time-integration of the upslope
water vapor flux (e.g., considering both the duration and intensity of upslope water
vapor flux) explains 74% of the variance in storm-total precipitation in the coastal
terrain of the Russian River watershed north of San Francisco (Ralph et al. 2013).
Spatial variability in either water vapor flux direction or watershed slope/aspect and
elevation can therefore influence the duration and intensity of upslope water vapor flux and result in spatial variability in storm-total precipitation within individual events from one watershed to the next (Hughes et al. 2014). For example, variability in water vapor flux direction of only a few degrees upon AR landfall resulted in extreme precipitation and localized flooding on the Pescadero Creek near Santa Cruz that did not occur among neighboring watersheds during a landfalling AR on 2–3 February 1998 (Ralph et al. 2003). Similarly, variability in water vapor flux direction or watershed slope/aspect and elevation may also greatly influence resultant runoff and streamflow (Neiman et al. 2011; Hughes et al. 2014).

This study is motivated by the few aforementioned studies that investigate the influence of water vapor flux magnitude and direction, often illustrated via the IVT vector or bulk upslope water vapor flux, during landfalling ARs on coastal California watershed precipitation. This study will expand upon these analyses of the IVT-related characteristics of landfalling ARs that may potentially influence spatial and temporal variability in precipitation, and in turn influence water resources and water resources management among all watersheds in California. Section 2 describes the data and methods, whereas section 3 contains the results of the study. Section 4 offers a concluding discussion of these results with application to California water resources and water resources management.
CHAPTER 2

2. Data and methods

The Parameter-elevation Regressions on Independent Slopes Model (PRISM) developed by Oregon State University is used for quantitative precipitation estimates (QPE) in this study (Daly et al. 1994, 2002, 2008). These data are a combination of point observations, a digital elevation model (DEM), and other geographical datasets that are modeled to generate a 4-km × 4-km gridded daily (ending at 1200 UTC) QPE. A variety of observational networks across California provide input data for PRISM, including remote automatic weather stations, the Community Collaborative Rain, Hail & Snow Network, snow telemetry stations, automated surface observing systems, and the U.S. Climate Reference Network. In order to estimate precipitation in data sparse regions, and potentially localized points within watersheds with complex topography, the PRISM model uses both “climatologically-aided interpolation” (1981–present) and the Advanced Hydrometeorological Prediction System (2002–present) to calculate a multi-factor physiographic-weighted climate-elevation regression (Daly et al. 1994; PRISM 2019). These factors include elevation, coastal proximity, topographic facet orientation, boundary layer exposure, topography, and orography (Luzio et al. 2008) which all may influence precipitation on scales <10 km (Daly et al. 1994; Daley 1991; Sharpes et al. 2005; Daly 2006) and may locally contain large errors (Bishop and Beier 2013). This study uses the daily 4-km PRISM QPE in order to calculate the daily mean areal precipitation (MAP) for each of the 140 Hydrologic Unit Code – 8 (HUC8)-sized watersheds in California (Fig. 1). The 4-km gridded dataset provides an average of 222 grid points within each of the 140
watersheds whose areal average likely mitigates any significant localized errors within any given watershed on any given day. Daily MAP is also summed by Water Year (WY), from October 1 to September 30, and averaged over the study’s 38-year (1982–2019) period to generate average annual MAP values and departures from the 38-year normal. Daily MAP extremes were defined as the top 5% of “wet” daily MAP days (i.e., >0 mm) over the entire 38-year period in each watershed.

The National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) Reanalysis (Saha et al. 2006) and CFS version 2 operational analysis (CFSv2) (Saha et al. 2014) datasets are used to calculate IVT along the coast of California following the methodology of Neiman et al. (2008a). The CFSR datasets are available four times daily with 0.5° latitude × 0.5° longitude grid spacing. We use these data at 25 grid locations every 0.5° from 30.0°N to 42.0°N along the California coast (Fig. 1) to create daily average IVT data for the 24-h period ending at 1200 UTC (e.g., average of the 1800 UTC, 0000 UTC, 0600 UTC, 1200 UTC times). For the purposes of relating IVT to landfalling ARs, this study defines an “AR day” as a day with daily average IVT magnitude values ≥250 kg m⁻¹ s⁻¹ at each of the 25 coastal grid points identified in Fig. 1, which is reliably similar (~96% match) to landfalling ARs using both magnitude and geometry-defined criteria in Rutz et al. (2014). In this study, we focus on IVT at coastal locations instead of collocated with inland watershed grid points in order to preserve maximum “ocean-inbound” IVT not contaminated by terrain or terrain effects (e.g., shadowing and/or barrier jets), to focus on the characteristics of
ARs at landfall, and to align with existing AR-related forecast tools that focus on IVT at similar coastal locations (e.g., Cordeira et al. 2017; Cordeira and Ralph 2021).

The relationship between ARs, IVT, and precipitation is investigated via two “maximum” Pearson squared ($r^2$) correlation values generated from time series of coastal daily average IVT and daily watershed MAP. The first maximum $r^2$ value for a watershed is the highest of the 25 $r^2$ values for the correlations between daily watershed MAP and the daily average IVT magnitudes at each coastal location. In other words, this first maximum $r^2$ value identifies the coastal location where IVT magnitudes explain the most variance in daily MAP for each watershed. This is the coastal location used to define AR frequency for a given watershed. The second maximum $r^2$ value for a watershed is the highest of 9,000 $r^2$ values for the correlations between daily watershed MAP and daily average projected IVT (IVTp) magnitudes at each location on the coast. The 9,000 $r^2$ values are a combination of the 25 coastal locations and projecting the IVT onto each possible direction between 0° and 359° (e.g., see example for North Fork Feather watershed in Fig. 2). This second maximum $r^2$ value identifies the coastal location where IVT magnitude and direction explain the most variance in daily MAP for each watershed. The aforementioned two maximum $r^2$ values are also calculated for the 850-hPa and 925-hPa water vapor flux to further investigate the elevation of lower tropospheric water vapor flux that explains the most variance in daily MAP for each watershed. The correlations and analyses in this study are also briefly summarized for the warm (April to September) and cool (October to March) seasons.
Figure 1. Map of California HUC8 watersheds (black lines) and topography (m; shaded) with coastal CFSR grid points (black circles) and the four focal watersheds (shaded; see legend) used and discussed in this study. The locations of the 12 Lakes/Reservoirs highlighted in Table 2 are denoted by triangles (see legend). Image created using QGIS 3.12 with topography and watershed boundaries obtained from the United States Geological Survey.
Figure 2. Correlation ($r^2$; shaded) values between daily projected IVT and watershed MAP for the North Fork Feather watershed as a function of coastal location (latitude) and IVT direction. The maximum $r^2$ value is marked by the black dot.
CHAPTER 3

3. Results

a. Watershed MAP climatology

The largest average annual MAP (>2000 mm) falls along the coastal western slopes of the Klamath Mountains in extreme Northwest California along the Oregon border, with MAP >1000 mm extending as far south as San Francisco Bay along the western North Coastal and northern Sierra Nevada Mountain Ranges (Fig. 3a). Examples of maximum average annual MAP within the study’s focal watersheds (see Fig. 1) include 1619 mm in the Upper Yuba and 1394 mm in the North Fork Feather watersheds, which are both located on the western slope of the Northern Sierra Nevada (Fig 4a, 4b), 1164 mm in the North-Coastal Russian River watershed (Fig. 4c), and 460 mm in the South-Coastal Santa Ana watershed (Fig 4d).

The contribution of extreme (top 5%) precipitation events to average annual MAP is largest in watersheds that receive less average annual MAP and smallest in watersheds that receive more average annual MAP (cf. Figs. 3a,b). The largest contributions from extremes to average annual MAP is >40% and occur locally across California in the Transverse Ranges (e.g., Santa Clara watershed), in the Colorado Desert (e.g., Salton Sea watershed), in the San Bernardino Mountains (e.g., Santa Ana watershed), near Lake Tahoe (e.g., Truckee and Upper Carson watersheds), and north of Mt. Whitney (e.g., Upper San Joaquin watershed) (Fig. 3b). The smallest contributions of extremes to average annual MAP is <25% and also occur locally across California near Los Angeles (e.g., Seal Beach watershed), the coastal Klamath Mountains (e.g., Chetco watershed), and in the northern Central Valley (e.g., Battle
Creek watershed). The contributions of extremes to average annual MAP is >33% for approximately half of all California watersheds, prominently located in the Sierra Nevada, Coastal Mountain Ranges, Mojave Desert, Peninsular Ranges, Transverse Ranges, San Bernardino Mountains, and San Gabriel Mtns (Fig. 3b). The average contributions to annual MAP by extreme events at the study’s four focal watersheds are 36%, 34%, 33%, and 42% in the Upper Yuba, North Fork Feather, Russian, and Santa Ana watersheds, respectively (Figs. 3b). The fraction of annual MAP by extreme events is directly correlated to the annual MAP in these watersheds with $r^2$ values of 0.88 in the Upper Yuba, 0.79 in the North Fork Feather, 0.82 in the Russian, and 0.92 in the Santa Ana watersheds (Fig. 4). In other words, variability in annual MAP is strongly influenced by variability in extreme events.

From another perspective, watersheds with less average annual MAP also require, on average, the least number of rainy days per year to accumulate half of their precipitation (Figs. 3a,c). Minima of 4 to 7 days located in southeast California correspond to regional minima in the average annual MAP, whereas maxima of 21–24 days located along the Oregon border correspond to regional maxima >1000 mm of average annual MAP. Values at the four focal watersheds include 16, 16, 13, and 7 days in the Upper Yuba, North Fork Feather, Russian, and Santa Ana watersheds, respectively.

**b. Relationships among ARs, coastal IVT, and watershed MAP**

Contributions to average annual MAP across California watersheds by precipitation on “AR days” is highest in northern California with >50% average
annual MAP falling on coastally-defined AR days (Fig. 3d). The maximum percentage of average annual MAP from precipitation on AR days is 71.5% at the Tomales-Drake Bays watershed northwest of San Francisco Bay that anchors a band of >60% values that extends east toward the Feather River watersheds in the Sierra Nevada (Fig. 3d). The minimum percentage of average annual MAP from precipitation on AR days is <25% and occurs in watersheds in the Mojave Desert and coastal Transverse Ranges (Fig. 3d). In the four focal watersheds, the average annual MAP from precipitation on AR days is 63%, 66%, 69%, and 43% in the Upper Yuba, North Fork Feather, Russian, and Santa Ana watersheds, respectively (Figs. 3d, 4, and 5). Precipitation on AR days in any given year is moderately correlated with annual MAP and annual MAP anomalies in these watersheds, explaining 68%, 58%, 49%, and 37% of the variance between these variables in the Upper Yuba, North Fork Feather, Russian, and Santa Ana watersheds, respectively (Fig. 5). For reference, the average annual frequency of landfalling AR days for these watersheds is 28, 28, 28, and 8 (Fig. 4).

The average statewide temporal correlation ($r^2$) between the daily IVT magnitude and daily watershed MAP for all 140 California watersheds is 0.34 (Table 1) with a range of ~0.50 in watersheds near the Klamath Mountains to ~0.10 in watersheds along the Colorado River (Fig. 6a). Widespread minima in this correlation value <0.30 exist across watersheds in southern California and maxima >0.40 exist across watersheds in northern California along the western Sierra Nevada from the Upper Tuolumne watershed to the North Fork Feather watershed (Fig. 6a). In other words, the daily IVT magnitudes along the coast explain at most ~50% of the variance in daily watershed MAP across California watersheds. When both the magnitude and
direction of daily IVT (i.e., IVTp) is accounted for in correlations with daily watershed MAP, correlation ($r^2$) values increase statewide by 0.11 on average to 0.45 (Fig. 6b and Table 1). Maximum correlation values increase in watersheds across northern and north-coastal California to ~0.50–0.65 and increase in watersheds across southern California to ~0.30 (Fig. 6b). At the four focal watersheds, the $r^2$ values increased by 0.15, 0.16, 0.15, and 0.09 in the Upper Yuba, North Fork Feather, Russian, and Santa Ana watersheds, respectively (Table 1). In summary, the daily projected IVT magnitudes that account for both IVT magnitude and direction along the coast explains ~30–65% of the variance in daily watershed MAP across California watersheds.

The coastal latitude location associated with the maximum correlation between daily projected IVT and daily watershed MAP is coastally ~2–3° south of the latitude of the respective watersheds (i.e., suggesting a southwest IVT; Fig 6c). The coastal IVT direction associated with the maximum correlation between daily projected IVT and daily watershed MAP ranges from 200° (approximately south-southwest) to 268° (approximately west) across the state (Fig 6d). Watersheds with maximum correlation values derived from southwesterly (~225°) IVT are predominately located along the coast (excluding locations near the San Francisco Bay Area Gap), whereas those derived from west-southwesterly (~245°) IVT are predominantly located across the Sierra Nevada (Fig. 6d). These west-southwest IVT directions are consistent with the predominant climatological southwesterly orientation of landfalling cool-season ARs (Neiman et al. 2008a).
The IVT is decomposed into isobaric water vapor flux in order to investigate the specific influence of lower-tropospheric water vapor flux on MAP and whether or not daily lower-tropospheric water vapor flux may explain a higher variance in daily MAP as compared to IVT. The daily average projected 850-hPa and 925-hPa water vapor fluxes generally result in a 0.0 to 0.20 increase in correlation ($r^2$) values with daily MAP as compared to the projected IVT $r^2$ values across California (Fig. 7 and Table 1). The correlation values are highest (>0.60) for both 850-hPa and 925-hPa water vapor fluxes in watersheds across the North Coast Ranges and inland along the western slopes of the Sierra Nevada Mountain Range (Figs. 7a, b). The highest correlation values >0.40 associated with the projected 850-hPa water vapor flux are constrained to the northern two-thirds of California (Fig. 7a), whereas the highest correlation values >0.40 associated with the projected 925-hPa water vapor flux extend into southern California (Fig. 7b). The lower-tropospheric projected water vapor fluxes explain a higher variance in daily MAP as compared to IVT predominantly across the Coastal Ranges and southern Sierra Nevada at 850 hPa and across most of southern California at 925 hPa (Figs. 7c, d). For example, the correlation value calculated using the projected 925-hPa water vapor flux increased from 0.36 to 0.60 in the Santa Ana river watershed over calculations using the projected IVT (Table 1). In the other three focal watersheds located in northern California, the 925- and 850-hPa water vapor flux correlation values were within 0.01 of each other and represented an increase of 0.03–0.07 over those values calculated using the projected IVT (Table 1). This analysis suggests that, for a majority of the state, the
more easily calculated lower tropospheric water vapor flux may explain more variance in daily watershed MAP than IVT.
Table 1. Summary of correlation ($r^2$) values between IVT, the projected IVT (IVTp), the 925-hPa water vapor flux (925F), the 850-hPa water vapor flux (850F), or the projected IVT during the cool season (IVTp-cool) with watershed MAP.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>IVT</th>
<th>IVTp</th>
<th>925 Flux</th>
<th>850 Flux</th>
<th>IVTp-cool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cali. Avg. (N=140)</td>
<td>0.34</td>
<td>0.45</td>
<td>0.52</td>
<td>0.51</td>
<td>0.54</td>
</tr>
<tr>
<td>North Fork Feather</td>
<td>0.46</td>
<td>0.61</td>
<td>0.65</td>
<td>0.65</td>
<td>0.69</td>
</tr>
<tr>
<td>Upper Yuba</td>
<td>0.44</td>
<td>0.60</td>
<td>0.66</td>
<td>0.65</td>
<td>0.68</td>
</tr>
<tr>
<td>Russian</td>
<td>0.48</td>
<td>0.63</td>
<td>0.66</td>
<td>0.66</td>
<td>0.71</td>
</tr>
<tr>
<td>Santa Ana</td>
<td>0.27</td>
<td>0.36</td>
<td>0.60</td>
<td>0.46</td>
<td>0.49</td>
</tr>
</tbody>
</table>
Figure 3. California watershed MAP climatology of (a) average annual MAP (mm), (b) percent of average annual MAP attributed to extreme events (%), (c) the number of days to receive half the average annual MAP (days), and (d) percent of average annual MAP attributed to AR days (%).
Figure 4. Annual summary of annual MAP (gray bars), annual MAP attributed to extremes (red bars; top 5% of rainy days), and percentage of annual MAP attributed to extremes (black line) for (a) the North Fork Feather watershed, (b) the Upper Yuba watershed, (c) the Russian watershed, and (d) the Santa Ana watershed for WY 1982–2019.
Figure 5. Annual summary of MAP anomaly (green and brown bars) and frequency of AR days (black line) for (a) the North Fork Feather River watershed, (b) the Upper Yuba River watershed, (c) the Russian River watershed, and (d) the Santa Ana River watershed for WY 1982–2019. The AR frequency derived from IVT data in (a,b) at 36.5°N, 122°W, in (c) at 37.5°N, 122°W, and in (d) at 32.5°N, 117.0°W.
Figure 6. California watershed maximum correlation values ($r^2$) for (a) IVT magnitude and watershed MAP and (b) projected IVT and watershed MAP. The coastal latitudes and IVT directions corresponding to the maximum correlations in (b) for each watershed are shown in panels (c) and (d).
Figure 7. California watershed maximum correlation values ($r^2$) for (a) projected 850-hPa water vapor flux and watershed MAP and (b) projected 925-hPa water vapor flux and watershed MAP, for comparison with the projected IVT and watershed MAP in Fig. 6b. The differences between the projected water vapor flux correlation values and the projected IVT correlation values are shown in (c) and (d).
CHAPTER 4

4. Concluding Discussion

This study summarizes both California watershed MAP and its relationship to coastal IVT, a common characteristic of landfalling ARs. The highest average annual MAP >2000 mm occurs in northern California watersheds with maxima >1500 mm extending south along both the Coastal and Sierra Nevada Mountain Ranges (Fig 3a). These maxima are associated with a higher annual frequency of precipitation events as illustrated by a larger number of days (>18 days) to receive half of their average annual MAP as compared to southern California watersheds (Fig. 3c). The minima in average annual MAP <300 mm occurs across watersheds in southern California and are associated with less frequent precipitation events as illustrated by a smaller number of days (<10 days) to receive half their average annual MAP. These climatological results summarized by watershed are consistent with previous studies that also show direct relationships between the frequency of precipitation events, the number of days to reach half the annual precipitation, and annual precipitation totals from individual observation sites across California by Dettinger et al. (2011) and Lamjiri et al. (2018).

The average annual MAP across California is influenced by extreme events with >35% of annual MAP in southern California watersheds falling on days when precipitation exceeds the top 5% of climatological wet days (Fig. 3a). The average annual MAP influenced by extreme events is less (~25%) in watersheds across northern California and is related to the higher number of days to reach half their annual precipitation as compared to southern California. Outside of the southern
deserts, the average annual MAP attributed to precipitation on “AR days” is ~30–50% with higher values in watersheds in the northern Sierra Nevada (Fig. 3d). The spatial variability in AR-related precipitation by watershed is directly related to latitudinal variability in the frequency of landfalling ARs (Rutz et al. 2014) and is also similar to results for precipitation and snow-water equivalent observations in California (Dettinger et al. 2011), the western U.S. (Rutz and Steenburgh 2012), and the Sierra Nevada (Guan et al. 2010).

Examination of the relationship between daily coastal IVT magnitude and watershed daily MAP illustrated highest correlation ($r^2$) values in coastal watersheds in northern and central California (~0.5) and the western slope of the Sierra Nevada (0.4–0.5) (Fig. 6a and Table 1). The lowest correlation values were located in watersheds over the southern Central Valley (0.2–0.3) and desert regions of southern California (<0.2) (Fig. 6a). These decreasing correlation values from north to south are likely related to the aforementioned decreasing frequency of landfalling ARs and the associated decrease in mean duration of enhanced IVT magnitudes from north to south over California (Rutz et al. 2014). Note that the lower correlation values in watersheds over northeast California (~0.35) are likely associated with the rain shadow effect from the upstream Klamath and Coastal Mountain Ranges (Smith 1979; Pandey et al. 1999; Smith et al. 2010; Lamjiri et al. 2018).

When both the magnitude and direction of IVT is accounted for using the projected IVT, the correlation values with watershed MAP increases by 0.11 on average across watersheds in California, with increases >0.15 in individual watersheds across northern and central California (Fig. 6b and Table 1). These results demonstrate
that both the magnitude and direction of IVT are important factors in describing the relationships between landfalling ARs and watershed precipitation on average, as confirmed by individual case studies (e.g., Neiman et al. 2011) and local studies in North-Coastal California (e.g., Ralph et al. 2013). Similarly, correlations between water vapor flux and watershed MAP demonstrate that the altitude of water vapor flux within the IVT distribution, specifically in the lower troposphere, is an additional important factor in describing the relationship between landfalling ARs and watershed precipitation. These results could help improve applications using IVT diagnostics associated with landfalling ARs to predict precipitation in California watersheds and also potentially improve the efficiency in calculating and producing these diagnostics by using isobaric water vapor flux in lieu of IVT.

The coastal latitude corresponding to the maximum correlation between the projected IVT and watershed MAP (Fig. 6c) demonstrated a southwest-to-northeast displacement similar to previous findings by Rutz et al. (2015), indicative of the climatological southwesterly IVT associated with landfalling ARs in California that produces inland orographic enhanced precipitation in California. The IVT direction corresponding to the maximum correlations between the projected IVT and watershed MAP (Fig. 6d) ranged from ~200° in watersheds in southeast California to ~270° in watersheds in northern California. Watersheds in the northern Sierra Nevada uniquely favored west-southwesterly (~245°) IVT directions with coastal latitudes near ~37°N (Figs. 6c,d) that suggested a preference for west-southwesterly water vapor transport along landfalling ARs through terrains gaps in the Coastal Ranges near the Petaluma and San Francisco Bay areas (Neiman et al. 2013b; Ralph et al. 2016) that may
produce inland orographic precipitation and/or interact with the Sierra Barrier Jet (Lundquist et al. 2010; Smith et al. 2010; Kingsmill et al. 2013; Neiman et al. 2013b; White et al. 2015; Ralph et al. 2016). Watersheds in southeast California also uniquely favored south-southwesterly (~210°) IVT directions with coastal latitudes near ~30–32°N (Figs. 6c,d) that suggested a preference for water vapor transport through terrain gaps in the Baja Peninsular Ranges (e.g., Rutz and Steenburgh 2012; Neiman et al. 2013a; Hughes et al. 2014; Rutz et al. 2015). In this case, however, the displacement of IVT far to the south of the region may not be representative of water vapor transport along an AR producing orographic precipitation within the desert regions of southeast California, but more-so representative of a synoptic-scale environment containing a cutoff low-pressure system producing inland precipitation while an AR coincidentally makes landfall in the Baja of California (e.g., Oakley and Redmond 2014; Oakley et al. 2018, 2020).

Given the climatological preference for variability in seasonal precipitation distributions across California related to cool-season ARs, vernal cutoff low-pressure systems (Oakley and Redmond 2014; Oakley et al. 2018, 2020), and warm-season North American Monsoon (NAM) surges and related convection (e.g., Adams and Comrie 1997, Ralph et al. 2014), we illustrate the correlations between the projected IVT and watershed MAP as a function of the warm (April to September) and cool (October to March) seasons (Figs. 8a,b and Table 1) and the associated IVT directions (Figs. 8c,d). These graphics demonstrate the primary utility of IVT magnitude and direction as a potential predictor of watershed MAP during the cool-season ($r^2$ values >0.60) with limited use in the warm season ($r^2$ values <0.10) when ARs and enhanced
IVT are less frequent. The associated warm-season IVT directions in southeast California are primarily south-southeast (~160°) and suggest that NAM surges of south-southeasterly lower-tropospheric water vapor flux from the Bay of California (e.g., Adams and Comrie 2017) or southeasterly mid-tropospheric water vapor flux through the Chiricahua Gap in the Continental Divide (Ralph and Galarneau 2017) into southeast California may contribute to a very small portion of the variance in daily watershed MAP. Given the limited role of IVT in watershed MAP in southeast California, and suggested limited role of orographic processes, it is likely that other factors related to synoptic and convective processes such as cutoff low-pressure systems (Oakley and Redmon 2014; Abatzoglou 2016) and other elements of the NAM (Adams and Comrie 2017), respectively, play a much larger role in modulating precipitation in these regions.

Altogether, the results of this study affirm that IVT magnitude and direction and the vertical distribution of water vapor flux are important factors in describing the relationships between landfalling ARs and watershed precipitation in California with annual \( r^2 \) values >0.60 and cool-season \( r^2 \) values near 0.70 in the focal watersheds in northern California in Table 1 (i.e., Upper Yuba, North Fork Feather, and Russian). This study expands upon a similar study on the relationship between observations of the bulk upslope water flux and storm-total precipitation in the Russian River watershed (Ralph et al. 2013; \( r^2 = 0.74 \)) and adopts a watershed framework to visualize the similar relationship between IVT and precipitation across California. The watershed framework lends itself to summarizing the results of this study for those watersheds which contain California’s largest reservoirs in order to provide situational
awareness in support of Forecast-Informed Reservoir Operations (Table 2). For example, Lake Oroville which contains two tributary HUC-8 watersheds (Middle Fork Feather and North Fork Feather) receives an average of ~65% of its annual MAP on “AR days” with annual maximum correlation ($r^2$) values >0.60 associated with enhanced coastal IVT at 36.5°N with a direction of ~238° (Table 2). These annual values increase to maximum correlation ($r^2$) values of 0.68–0.69 with similar coastal IVT characteristics during the cool season (Table 2). From a water resource management perspective, this information may provide valuable situational awareness when using AR-related forecast tools in the decision-making process of releasing or storing water in advance of a landfalling AR. Future work is aimed at using the results of this study to motivate and inform the future development of AR-related forecast tools and to further explore those factors which influence watershed MAP and streamflow in addition to IVT and water vapor flux.

**Data Availability Statement**

Data analyzed in this study were a re-analysis and derivation of existing data, which are openly available at locations cited in the data and methods section.
Table 2. Summary of results for the HUC8 watersheds containing 12 California Lakes/Reservoirs, listed from north to south.

<table>
<thead>
<tr>
<th>Name</th>
<th>Watershed(s)</th>
<th>Percent of Annual from AR days (%)</th>
<th>IVT &amp; MAP Correlation ($r^2$)</th>
<th>Projected IVT &amp; MAP Correlation ($r^2$)</th>
<th>Latitude of max correlation (°)</th>
<th>IVT Direction of max correlation (°)</th>
<th>Proj. IVT &amp; MAP cool-season corr. ($r^2$)</th>
<th>Latitude of max cool-season corr. (°)</th>
<th>IVT Direction of max cool-season corr. (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trinity Lake</td>
<td>Trinity</td>
<td>53</td>
<td>0.51</td>
<td>0.65</td>
<td>38.5</td>
<td>226</td>
<td>0.74</td>
<td>38.5</td>
<td>231</td>
</tr>
<tr>
<td>Shasta Lake</td>
<td>Sacramento Headwaters</td>
<td>59</td>
<td>0.45</td>
<td>0.62</td>
<td>38.0</td>
<td>219</td>
<td>0.69</td>
<td>38.0</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>McCloud</td>
<td>59</td>
<td>0.47</td>
<td>0.63</td>
<td>37.5</td>
<td>224</td>
<td>0.71</td>
<td>38.0</td>
<td>223</td>
</tr>
<tr>
<td></td>
<td>Lower Pit</td>
<td>59</td>
<td>0.49</td>
<td>0.64</td>
<td>37.5</td>
<td>231</td>
<td>0.73</td>
<td>37.5</td>
<td>233</td>
</tr>
<tr>
<td>Lake Oroville</td>
<td>Middle Fork Feather</td>
<td>64</td>
<td>0.43</td>
<td>0.60</td>
<td>36.5</td>
<td>239</td>
<td>0.68</td>
<td>36.5</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>North Fork Feather</td>
<td>66</td>
<td>0.46</td>
<td>0.61</td>
<td>36.5</td>
<td>236</td>
<td>0.69</td>
<td>37.5</td>
<td>233</td>
</tr>
<tr>
<td>New Bullards Bar Reservoir</td>
<td>Upper Yuba</td>
<td>63</td>
<td>0.44</td>
<td>0.61</td>
<td>36.5</td>
<td>241</td>
<td>0.68</td>
<td>36.5</td>
<td>245</td>
</tr>
<tr>
<td>Lake Mendocino</td>
<td>Russian</td>
<td>69</td>
<td>0.48</td>
<td>0.63</td>
<td>37.5</td>
<td>220</td>
<td>0.71</td>
<td>37.5</td>
<td>222</td>
</tr>
<tr>
<td>Folsom Lake</td>
<td>North Fork American</td>
<td>37</td>
<td>0.41</td>
<td>0.58</td>
<td>36.0</td>
<td>247</td>
<td>0.65</td>
<td>36.0</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>South Fork American</td>
<td>39</td>
<td>0.42</td>
<td>0.58</td>
<td>35.5</td>
<td>250</td>
<td>0.65</td>
<td>35.5</td>
<td>252</td>
</tr>
<tr>
<td>Don Pedro Reservoir</td>
<td>Upper Tuolumne</td>
<td>39</td>
<td>0.41</td>
<td>0.59</td>
<td>35.0</td>
<td>246</td>
<td>0.66</td>
<td>35.0</td>
<td>248</td>
</tr>
<tr>
<td>San Luis Reservoir</td>
<td>M. San Joaquin-L. Chowchilla</td>
<td>40</td>
<td>0.35</td>
<td>0.51</td>
<td>35.0</td>
<td>236</td>
<td>0.58</td>
<td>35.0</td>
<td>237</td>
</tr>
<tr>
<td>Pine Flat Reservoir</td>
<td>Upper King</td>
<td>43</td>
<td>0.37</td>
<td>0.50</td>
<td>34.5</td>
<td>237</td>
<td>0.58</td>
<td>34.0</td>
<td>237</td>
</tr>
<tr>
<td>Isabella Lake</td>
<td>Upper Kern</td>
<td>21</td>
<td>0.32</td>
<td>0.39</td>
<td>33.5</td>
<td>251</td>
<td>0.48</td>
<td>33.5</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>South Fork Kern</td>
<td>22</td>
<td>0.33</td>
<td>0.37</td>
<td>33.5</td>
<td>242</td>
<td>0.48</td>
<td>33.5</td>
<td>240</td>
</tr>
<tr>
<td>Lake Havasu</td>
<td>Havasu-Mohave Lakes</td>
<td>20</td>
<td>0.12</td>
<td>0.19</td>
<td>30.0</td>
<td>219</td>
<td>0.32</td>
<td>30.0</td>
<td>218</td>
</tr>
<tr>
<td>Prado Flood Control Basin</td>
<td>Santa Ana</td>
<td>43</td>
<td>0.27</td>
<td>0.37</td>
<td>32.5</td>
<td>226</td>
<td>0.49</td>
<td>32.5</td>
<td>219</td>
</tr>
</tbody>
</table>
Figure 8. California watershed maximum correlation values ($r^2$) for projected IVT and watershed MAP in (a) the April to September warm season and (b) the October to March cool season, for comparison with the projected IVT and watershed MAP in Fig. 6b. The IVT directions corresponding to the maximum correlations in (a) and (b) for each watershed are shown in panels (c) and (d). Note that the colors for IVT directions on panels (c) and (d) differ from those colors for IVT directions in Fig. 6d.
REFERENCES


Cordeira J. M., J. Stock, M. D. Dettinger, A. M. Young, J. F. Kalansky, and F. M. Ralph, 2019: A 142-year climatology of northern California landslides and


Hecht C. W., and J. M. Cordeira, 2017: Characterizing the influence of atmospheric river orientation and intensity on precipitation distributions over North Coastal


Lamjiri M. A., M. D. Dettinger, F. M. Ralph, N. S. Oakley, and J. J. Rutz, 2018: Hourly analyses of the large storms and atmospheric rivers that provide most of California’s precipitation in only 10 to 100 hours per year. *San Franc. Estuary Watershed Sci.*, **16**, https://doi.org/10.15447/sfews.2018v16iss4art1


Neiman P. J., F. M. Ralph, G. A. Wick, J. D. Lundquist, and M. D. Dettinger, 2008a: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations. *J. Hydrometeor.*, 9, 22–47, https://doi.org/10.1175/2007JHM855.1


Oakley N. S., J. T. Lancaster, B. J. Hatchett, J. Stock, F. M. Ralph, S. Roj, and S. Lukashov, 2018: A 22-Year climatology of cool season hourly precipitation


