Wintertime Extreme Precipitation Events along the Pacific Northwest Coast: Climatology and Synoptic Evolution

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Extreme precipitation events impact the Pacific Northwest during winter months, causing flooding, landslides, extensive property damage, and loss of life. Outstanding questions about such events include whether there are a range of associated synoptic evolutions, whether such evolutions vary along the coast, and the rainfall duration and variability during extreme precipitation events. To answer these questions, this study uses 60 years of National Climatic Data Center (NCDC) daily precipitation observations to identify the top 50 events in two-day precipitation at six coastal stations from northern California to northwest Washington. NCEP/NCAR reanalysis data were used to construct synoptic composite evolutions of these events for each coastal location. It is found that most regional flooding events are associated with precipitation over 24 hours or less, and that two-day precipitation totals identify nearly all major events. Precipitation distributions of major events are generally narrow, roughly 200 km in width, and most are associated with atmospheric river events, with negative anomalies in sea-level pressure and upper-level height in the central Pacific, high-pressure anomalies over the southwest U.S., large positive 850 hPa temperature anomalies, and enhanced precipitable water and integrated moisture flux over southwest to northeast swaths. A small subset of extreme precipitation events over the southern portion of the domain is associated with a very different synoptic evolution: a sharp trough in northwesterly flow and post-cold-frontal convection. High precipitable water values are more frequent during the summer but are not associated with heavy precipitation due to upper-level ridging over the eastern Pacific and weak onshore flow that limit upward vertical velocities.
1. Introduction

The northwest United States frequently experiences extreme precipitation events during the winter months, with some resulting in billions of dollars of damage as well as loss of life. Since 1955, these storms were responsible for roughly two thirds of the presidential disaster declarations in Washington State and Oregon, and nearly one quarter of the declarations in California.¹ For example, during December 1996 and January 1997, heavy rain (25-100 cm in two weeks) produced severe flooding over portions of California, Washington, and Oregon, causing 3.9 billion dollars in losses and 36 deaths.² More recently, heavy rainfall and resulting flooding during January 2009 closed Interstate 5 and other major routes in Washington State, flooded major river drainages throughout the Northwest, and heavily damaged the Howard Hanson Dam in the Washington Cascades, putting 10-20 billion dollars of assets and infrastructure, as well as tens of thousands of people, at risk (Mastin and Barnas 2010; Neiman et al. 2011).

Most extreme precipitation events along the North American west coast are associated with narrow plumes of above-normal water vapor that stretch from the subtropics or tropics to the coast and are often referred to as atmospheric rivers (AR). In a seminal paper on the topic, Zhu and Newell (1998) found that greater than 90% of the hemispheric meridional moisture flux is transported by such features, with four to five evident at any given time. AR moisture is often quickly converted to heavy precipitation upon landfall on coastal and inland mountain ranges, inundating local watersheds and causing severe flooding in low-lying areas (Ralph et al. 2006; Stohl et al. 2008; Viale and Nunez 2010; Dettinger et al. 2011; Neiman

¹http://www.fema.gov/news/disasters.fema
²http://www.ncdc.noaa.gov oa/reports/billionz.html
et al. 2011).

Some studies have suggested that anthropogenic global warming could impact the severity and frequency of extreme precipitation events in the future (Groisman et al. 2005; Held and Soden 2006; Trenberth et al. 2007). It has been theorized that changes in equator-to-pole temperature gradients (Yin 2005) and Hadley Cell expansion could push the storm track poleward in the Northern Hemisphere (McCabe et al. 2001; Hu and Fu 2007; Lu et al. 2007; Meehl et al. 2007). Such changes could potentially have a large impact on precipitation in the Pacific Northwest and California (Salathe 2006; Dettinger 2011; Mass et al. 2011) since ARs are generally on the southern flank of the jet stream. A thorough understanding of the synoptic conditions conducive to extreme precipitation events along the west coast of North America is essential for making future projections under climate change.

A series of major floods over the western U.S. during the 1980s and 1990s stimulated research on the nature of heavy precipitation over the region. Lackmann and Gyakum (1999) examined the composite synoptic evolution associated with 46 heavy precipitation events over Washington State in which each of four observing sites received at least 12.5 mm (∼0.5 inches) of daily precipitation. Composites of 500 hPa geopotential heights indicated a positive anomaly over the Bering Sea prior to such events, with a negative height anomaly over the Gulf of Alaska and ridging over the southwest U.S. resulting in strong southwesterly flow approaching the Pacific Northwest. Using a piecewise potential vorticity (PV) analysis for one event, this paper found a dominant contribution to moisture transport by mobile cyclonic disturbances rather than planetary-scale flow. Ralph et al. (2004) used aircraft dropsonde observations during the California Land-falling Jets (CALJET) Experiment to demonstrate the relatively narrow, shallow nature of AR moisture plumes and their close
association with the low-level jets in the warm sector preceding cold fronts. These findings were confirmed by compositing satellite-observed microwave data. Dettinger (2004) used National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data from 1948 to 1996 to identify 206 days with moisture flux signatures similar to those found during AR events. He found that all events occurred between October and April, with a peak in January and February, and were associated with warmer and wetter conditions than normal. Neiman et al. (2002) studied the relationship of the speed and height of the AR-related low-level jet and coastal mountain precipitation, while Neiman et al. (2005) examined the relative importance of bright band and non-bright band precipitation on coastal terrain. Ralph et al. (2005) used dropsonde observations from CALJET-1998 and the Pacific Land-falling Jets Experiment (PACJET-2001) to study the structure of eastern Pacific AR events and their inter-annual variability for two different phases of ENSO.

More recently, Ralph et al. (2006) found that ARs were associated with seven floods on California’s Russian River. They suggested that not all ARs produce flooding, with flooding requiring antecedent soil saturation, intense precipitation, and ARs remaining over a watershed for an extended period. Bao et al. (2006) found that local moisture convergence was a key process in the formation of simulated moisture plumes, although long-distance transport of tropical moisture was possible in some cases. Neiman et al. (2008a) established a climatology of West Coast ARs using satellite-based integrated water vapor (IWV) for 1997 through 2005. In this paper they examined the synoptic conditions of north coast (WA, OR, and BC) and south coast, (CA) ARs. They found ARs in all seasons, with warm season events bringing little precipitation. AR water vapor signatures greatly outnumbered heavy
precipitation and flooding events, suggesting that ARs are necessary, but not sufficient, for extreme precipitation situations. Neiman et al. (2008b) used the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) to examine the November 2006 AR event that devastated areas of Washington and Oregon, revealing similar structures to past events studied using dropsonde and reanalysis data. Roberge et al. (2009), studying large integrated water vapor events over the west coast of Canada, found a range of possible air trajectories, with southwest trajectories associated with the largest precipitation events. Neiman et al. (2011) used several decades of daily stream flow data from unregulated rivers in Washington State and North American Regional Reanalysis (NARR) to examine synoptic conditions leading to flooding in those watersheds. Most flooding events were found to be associated with AR conditions with either westerly or southwesterly flow. The top 10 annual peak daily flows on all watersheds were accompanied by heavy precipitation, low-level moist neutral static stability, and elevated freezing levels.

Although much work has been done to understand West Coast extreme precipitation events, many important questions still remain and are considered in this paper: 1) How long do extreme precipitation events that cause high river flows last and what are the characteristics of their temporal evolution? 2) How does the large-scale synoptic structural evolution associated with extreme precipitation events change with latitude along the coast? 3) Are there synoptic conditions other than atmospheric rivers that can cause extreme coastal precipitation, and if so, what are these alternate evolutions and how frequently do they occur? 4) What is the typical horizontal scale associated with extreme precipitation events? Although there is a substantial literature on West Coast precipitation and atmospheric river events, many of these questions have not been addressed.
To evaluate the temporal evolution of such heavy precipitation events, 60 years of hourly National Climatic Data Center (NCDC) precipitation records at two stations along the Oregon coast were examined. To define extreme precipitation events and to establish the climatology of these events over the last 60 years, NCDC daily precipitation observations from six coastal stations from northwest Washington to northern California are used. Composites and composite evolutions of synoptic variables are created for the top 50 events at each station to determine differences along the coast, and the individual evolutions are examined to determine their variability. Finally, the synoptic scale evolutions for heavy precipitation events that occurred in the absence of an AR are examined.

2. Event definition and temporal variation

This study is based on a series of relatively evenly spaced coastal stations in the Pacific Northwest. Specifically, NCDC Global Historical Climatology Network (GHCN) daily precipitation observations from 1950-2009 for six coastal stations from northern Washington State to northern California (Figure 1) were used to identify extreme precipitation events. The farthest north station, Forks (FORW1), is located in the northwest corner of Washington State, west of the Olympic Mountains. Four of the stations are located in Oregon, including Astoria (KAST), Newport (KONP), North Bend (KOTH) and Brookings (K4BK). Astoria and Newport have relatively low coastal terrain to their east, while North Bend and Brookings are west of the higher Klamath Mountains. Finally, Eureka (KEKA) is located along the northern California coast, with the relatively high terrain of the South Fork Mountains to the east. These stations were chosen due to their close proximity to the coast, a relatively
long period of record, even latitudinal spacing, and an absence of upwind terrain, which can
lead to modulation by rain shadowing.

A key question regards the duration of precipitation events causing flooding over the
region. Several recent storms in the Pacific Northwest, such as November 2006, December
2007, and January 2009, have produced flooding on Washington and Oregon rivers in as-
association with precipitation events of one to three days.\(^3\) The “time of concentration” is
the time required for a significant rise in river level after rain begins at a significant rate
(usually around 0.50-0.75 cm (0.2-0.3 inches) of rain per hour) over a basin and is gener-
ally less than 24 hours for the Northwest U.S. rivers examined in this study (Larry Schick,
U.S. Army Corps of Engineers, Northwest region, lead forecaster, private communication;
Dennis Lettenmeier, University of Washington, Department of Civil Engineering, private
communication).\(^4\)

To further examine the appropriate period of precipitation correlating best with river
levels, U.S. Geological Survey (USGS) average daily river discharges for naturally flowing
rivers along the West Coast were compared to daily precipitation from the GHCN data
set. Daily values were used since very few observing sites offer continuous long-term hourly
precipitation or hourly river levels. It is important to note that one-day GHCN values are
potentially problematic since extreme precipitation events could span calendar days. At
each of the six coastal precipitation sites, one- through four-day precipitation totals were
correlated with the mean daily river gauge discharge on free-flowing rivers for lags of zero,

\(^3\)NCDC Storm Events database:
http://www4.ncdc.noaa.gov/cgi-win/wwwgi.dll?wwEvent˜Storms

\(^4\)Time of concentration was very roughly estimated by dividing the square root of the area of the drainage
basin (an integer multiple of basin linear distance) by a channel flow of \(\sim 1\) m/s. (Dennis Lettenmeier, Uni-
versity of Washington, Department of Civil Engineering, private communication)
one, two, and three days. For all precipitation sites, the highest correlations were with a nearby river.

Table 1 shows the average correlations (for all six precipitation sites) of all combinations of lag and precipitation period. For all lags, the 24-hour period had the lowest correlations, undoubtedly due to the event splitting (calendar day) issue noted above. The correlations are highest for the 72-hour period, with the 48-hour period close behind. There were high correlations for zero- and one-day lags and a fairly rapid decline for longer lags. These results suggest that relevant precipitation period for hydrologically meaningful events is one or two days. First, the relevant period is clearly greater than a few hours, since the 24-hour period has weaker correlation. Secondly, the fact that the correlations are relatively constant for 48 hours and greater, suggests that 48 hours contains the most relevant precipitation amounts. Furthermore, the substantial drop-off for a greater than one-day lag suggests that precipitation several days before is not relevant. Thus, based on both the physical nature (response time) of Northwest drainages, our analysis of the correlations between precipitation and river flow, and the availability of daily precipitation data, two-day total precipitation was used to define extreme events in this study. Furthermore, only the cool, wet season (October-March) was considered since flooding is extremely rare during the warm season in this region.

Daily GHCN precipitation totals were used to find the top 50 two-day events at each of the six stations (Figure 1). Dates were eliminated if they were within five days of an event with greater precipitation, ensuring that each event represented a distinct synoptic situa-

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5 The last day of the multi-day periods was used as the value for correlations.
6 The reporting times of the precipitation reports vary by station.
tion. Additionally, the data were quality controlled to eliminate days with large daily totals following days with missing data, since the resulting large totals are usually not associated with a major event, but rather indicative of equipment malfunction or observer absence. As a check on the validity of the two-day event assumption, the top 50 one- and three-day events were also determined from the same, quality controlled data set. A nearly identical list of events was determined.

As noted earlier, coastal stations were used in this analysis to reduce the potential of mesoscale modulation of precipitation intensity that would be unrepresentative of regional precipitation. To further explore the applicability of coastal stations, the NOAA Climate Prediction Center (CPC) quarter-degree Daily U.S. Unified Precipitation Dataset (Higgins and Yao 1996) for 1950-2009 was used to examine precipitation spatial correlations associated with the 50 extreme two-day precipitation events at the selected coastal stations.\(^7\)

Specifically, the top 50 extreme two-day precipitation at coastal stations was correlated with temporally coincident two-day gridded precipitation across the region (Figure 2). High correlations surround each station on a southwest-northeast axis at every location except Newport, whose swath was oriented more west-east, and Forks, which lies at the northern boundary of the analysis domain. Most stations show strong anti-correlations over adjacent areas, particularly to the south, where there is generally suppression of precipitation by high pressure located to the southeast of ARs. As described below, the high pressure helps provide the large height gradients and thus strong onshore flow required for major events.

Terrain enhancement can be seen in the correlation plots, such as over the Cascades and

\(^7\)CPC U.S. Unified Precipitation data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/
the Olympic Mountains in the Forks and Astoria maps (Figure 2a, b). Some areas of low correlation, such as over Puget Sound for heavy precipitation events at Forks, are associated with large variability of precipitation during extreme events due to mesoscale variations in rain shadowing. Other areas, such as eastern Washington, are nearly always dry and thus show relatively low correlations. The swaths of high correlation are relatively narrow, \(~200\) km wide, consistent with the narrow nature of ARs described in the literature (e.g., Ralph et al. 2004). The structure of the spatial correlations between coastal time series of precipitation with gridded analyses for extreme precipitation events (Figure 2) is noticeably different than the correlations for all precipitation intensities (Figure 3). Considering all precipitation events, there are large areas of high positive correlation surrounding each station with very little structure, and no adjacent zones of negative correlation. This suggests that more typical precipitation events have a broader structure than extreme events (such as those associated with ARs), or are associated with a range of possible evolutions.

The amount of two-day coastal precipitation varies substantially among the top 50 events (Table 2). The two-day precipitation for the #1 ranked storm ranged from 31.0 cm (12.21 inches) at Forks, WA, to 16.6 cm (6.55 inches) at Astoria, OR. The #50 ranked storm ranged from 15.8 cm (6.23 inches) at Forks, WA, to 7.72 cm (3.04 inches) at Eureka, CA. The gauges at Forks, North Bend, Brookings, and Eureka have relatively high terrain to the east, resulting in increased precipitation from topographic enhancement for the most extreme events. In contrast, Astoria and Newport have lower terrain nearby, and thus generally smaller two-day totals for the top ranked storms. The two-day totals were highest for the #50 ranked storms at the stations upwind of the highest terrain (Forks and Brookings).

Searching for the top 50 events in two-day precipitation at each coastal station produced a
total of 207 events (several appear in the top 50 for multiple stations). The majority of these events occurred in November, December, and January (Figure 4a), similar to the results of Neiman et al. (2008a) and Lackmann and Gyakum (1999). Examining decadal variability, the 1960s, 1970s, and 2000s experienced relatively few extreme precipitation events, while the 1950s, 1980s, and 1990s received more (Figure 4b). Similar decadal variability was found using extreme one- and three-day precipitation totals (not shown). This decadal modulation is consistent with previous studies that found strong Pacific and Atlantic storm tracks in the 1950s, 1980s, and 1990s, and relatively weaker storm tracks during the 1960s and 1970s (Chang et al. 2002; Chang and Fu 2002).

While daily precipitation is useful, it lacks sufficient temporal resolution to evaluate the detailed evolution of extreme precipitation events. At two of the above stations, Astoria and Brookings, hourly precipitation data were available from NCDC for most of 1950-2009 and was used to examine the evolution and durations of the top 50 storms defined by the two-day totals. In the Pacific Northwest during winter months, it is common for some locations to receive persistent rain for days or weeks without flooding. It is therefore necessary to separate the extreme events from the background precipitation in order to examine storm duration and evolution. To ensure that we included the entire storm for each of the top 50 events, two days were added before and after the two-day periods noted above to create a six-day examination period for each event.

Table 3 shows the average periods associated with various percentages of the six-day storm totals at Astoria and Brookings. The results at both stations are very similar, with 50% to 95% of the storm total precipitation occurring over periods of roughly 20 to 90 hours. Arbitrarily choosing 75% of the six-day total as the definition of storm duration,
the average storm length was 44 and 45 hours at Astoria and Brookings, respectively. The shortest and longest “storms” were 16 (17) and 86 (82) hours at Astoria (Brookings) by this 75% definition. Plotting a histogram of storm lengths at these two locations using the 75% criterion (Figure 5) indicates considerable variability in the storm periods, with little evidence of a dominant mode. Thus, although the time of concentration for most Northwest drainages is less than 24 hours, a period similar to the shortest storms noted in Table 3, many storms had significant precipitation over one to three days. Examining individual storms, there is considerable variability in their temporal evolutions (Figure 6). Some storms experience heavy rain in one spike, some in several spikes. Others receive moderate rain for many hours, without large spikes.

3. Synoptic structure and evolution

Although some studies have examined composites of the synoptic flow associated with heavy precipitation affecting the U.S. West Coast (Lackmann and Gyakum 1999; Neiman et al. 2008a), few have examined how the synoptic evolution associated with such events vary along the coast. Some insight into this issue is found in Neiman et al. (2008a), which looked at the synoptic conditions associated with major AR events for two large spatial areas: the entire Pacific Northwest (including southern B.C.) and California. The study presented below examines how synoptic evolution associated with heavy precipitation events varies progressively along the coast using six stations from northern Washington to northern California, without the assumption that all events must be associated with ARs. Furthermore, we have examined each event individually to determine the range of synoptic evolutions
associated with major precipitation events.

The NCEP/NCAR six-hour reanalysis data (Kalnay et al. 1996) for precipitable water, 500 hPa and 700 hPa geopotential heights, sea level pressure, and 850 hPa temperature, were used to composite the synoptic evolution of the top 50 two-day precipitation events. Each event is compared to the 60-year climatology for the corresponding days and the anomalies from climatology for each event were averaged to create an anomaly composite. These fields are assumed to have approximately normal distributions and the Student’s $t$ statistic is used to identify areas that are statistically different from climatology at the 95% level. Since the extreme precipitation dates were based on a two-day cumulative total, it was necessary to identify a “0” time for the composites. If one of the two one-day totals was more than double the other, then the grid time closest to the middle of that precipitation day was used. If not, the grid time between the two precipitation days was used. Composites of synoptic variables were made every six hours for three days before and after the “0” time for each of the six stations. Due to similarities among adjacent stations, only three of the six stations, Forks, Newport, and Eureka, are shown.

At the time of maximum precipitation the 500 hPa (not shown) and 700 hPa composite geopotential height anomalies (Figure 7) are negative to the northwest (ridging) and positive to the southeast (troughing) of each station, with the anomalies shifting progressively with station position. The negative anomalies are a factor of two greater than the positive anomalies at all stations except North Bend and Eureka (Figure 7c), where the factor increased to three to four. At Forks, the negative anomaly extends farther west than those of

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$^8$NCEP Reanalysis derived data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/
the other stations. The sea-level pressure anomalies (not shown) possess similar features to these upper level patterns. At all stations, the flow at all levels is generally southwesterly, although the flow at Forks contains more of a southerly component than the other stations.

850 hPa temperature anomalies along the coast and the near-shore waters are large, positive and spatially extensive at Forks (Figure 8a), reaching approximately +6°C at the time of heaviest precipitation. At stations to the south, the positive anomalies substantially weaken (to 2-3°C), shift southward, and are displaced mainly equatorward of the locations in question (Figures 8b, c). At all stations, significant negative anomalies are seen to the northwest of the observing site, with the magnitude of these anomalies increasing for the southern locations.

At the time of heaviest coastal precipitation there is much higher than normal precipitable water values extending southwest off the coast and inland to the northeast from each station (Figure 9). The largest positive anomalies (10-15 mm) are located southwest of each station and suggest an AR signature (Lackmann and Gyakum 1999; Ralph et al. 2004, 2006; Junker et al. 2008; Neiman et al. 2008a). At all stations, there are significant negative anomalies to the north and south of the moisture plume. There is a progressive southward shift and widening of the positive anomalies for stations farther southward down the coast.

Individually, the precipitable water and height/wind fields show large anomalies with coherent structure, and this is reflected in the combination of the two, integrated moisture flux (IMF). Here, IMF is defined as \( \bar{q} \times \bar{U} \times dp/g \), vertically integrated to 300 mb (Neiman et al. 2008a), where \( \bar{q} \) is mean specific humidity between adjacent layers, \( \bar{U} \) is the mean magnitude of the combination of the horizontal wind vectors \( u \) and \( v \) between adjacent pressure levels, \( dp \) is the pressure difference and \( g \) is acceleration due to gravity. At each grid point, these
values were summed from 1000 to 300 hPa to yield IMF in \( km m^{-1} s^{-1} \). At all of the stations, anomalously high IMF is seen extending southwest from the Pacific Northwest coast into the subtropical central Pacific (Figure 10), with the maxima shifting spatially for the southern stations. The positive precipitable water anomalies turn westward and pass immediately north of Hawaii. The 850 hPa wind vector anomalies indicate enhanced southwesterly flow in the middle of the flux maxima, as well as enhanced northerlies over the Gulf of Alaska. There is confluence of the 850 hPa winds along the entire length of the IMF maxima.

In order to examine the evolution of the synoptic fields associated with heavy precipitation events, anomaly composites for several variables were made for each station every six hours for three days before and after the time of maximum precipitation (time 0). In the interest of space, only composite evolutions at Forks and Eureka, the stations farthest north and south, are shown (Figures 11-14). At 500 hPa, there are notable differences in the evolution of the geopotential height anomalies between the two stations, although both start with a region of negative anomalies stretching from the central Pacific to the northwest U.S., British Columbia, and southeast Alaska (Figure 11), and no positive anomalies to the south. Forks begins with a larger negative height anomaly over the central Pacific Ocean, and a smaller one near the coast. Two days prior to the heaviest precipitation, Forks has a far deeper anomaly over the central Pacific, while Eureka has an extensive weak positive anomaly over the south portion of the domain. At one day prior, the negative anomaly for Forks is deepest to the south of the Gulf of Alaska and is displaced considerably westward of the negative anomaly at Eureka; at the same time Forks has developed a modest positive anomaly over the U.S. west coast. At time 0, the negative anomalies are deepest, the Forks anomaly is located in the Gulf of Alaska (Figure 11d), and the Eureka anomaly is
found offshore near Vancouver Island (Figure 11h). The positive anomaly is larger at Forks and covers the entire western U.S., whereas the positive anomaly for Eureka is located over the southwest U.S. In summary, the negative height anomalies at 500 hPa for Eureka were nearly stationary and increased in amplitude in time as positive anomalies developed over the southwest. In contrast, the synoptic evolution at Forks was far more dynamic, with dual negative maxima; the one over the central Pacific moved eastward and amplified into the dominant feature as positive anomalies developed in place over the Southwest.

At the surface, the sea-level pressure evolution is very similar to the upper-level development (Figure 12). However, at the surface the central Pacific negative anomaly was even more dominant for the sea-level pressure evolution at Forks, and the positive anomaly was relatively weaker. Thus, at Forks there is a strong suggestion of the importance of a westward-moving feature in heavy precipitation events, while at Eureka the amplification of a pre-existing trough appears more significant.

The 850 hPa temperature evolutions also show significant differences among the stations (Figure 13). At the two northern stations, Forks and Astoria, there are weak (1-2°C) positive 850 hPa temperature anomalies over the central Pacific at -72 hours that amplify and move to the West Coast during the next three days. In contrast, at Eureka there is little evidence of the eastward movement of positive anomalies over the Pacific, rather a modest positive anomaly (far weaker than the one for Forks and Astoria) develops during the last day of the event. All stations had a negative temperature anomaly offshore during the period of heaviest precipitation; for Forks there was some suggestion of the eastward movement of a feature, while for Eureka the negative anomaly developed in place. It is interesting that the positive temperature anomalies near the time of the event are far more widespread than the
precipitable water or integrated moisture flux anomalies (Figures 9, 10).

The evolutions of the precipitable water composites reflect the varying developments between the northern and southern coastal locations (Figure 14). At Forks, an amorphous and weak area of positive anomalies strengthens and moves westward during the three days. During that period, the positive anomaly becomes narrower and more focused, with negative anomalies developing and moving eastward to the north and south. For Eureka, the pattern appears to develop in place as a core of positive anomalies and adjacent negative anomalies increase in time. Composite integrated moisture flux anomalies generally mirror the precipitable water anomaly fields and thus are not shown.

4. Alternate synoptic evolutions

a. Non-AR extreme precipitation

The composites of the top 50 storms for each of the six stations and the inspection of each individually suggest that most are associated with extensive water vapor transport from the subtropics and tropics that typify ARs. However, there is a small subset of heavy coastal precipitation events that rank among the top 50 that are not associated with ARs. These events occur only at three of the southern stations: Newport, North Bend, and Eureka. The infrequent occurrence of non-AR storms means that they are not represented in the synoptic composites; thus, it is necessary to take a closer look at these storms individually.

One such event occurred on 13-15 March 1967 when 10.97 cm (4.32 in) of rain fell at Newport (the 27th greatest two-day wintertime precipitation total at that location). For
these two days, the synoptic pattern included a stationary high-amplitude, short-wave trough offshore at 700 hPa (Figure 15a) and 500 hPa (not shown), and an offshore surface low (Figure 15b) that deepened substantially in the first 24 hours and weakened in the last 24 hours (not shown). In addition, there were negative 850 hPa temperature anomalies over the entire coast (Figure 15c) and negative precipitable water anomalies along the Oregon coast (Figure 15d).

This case and the four other non-AR heavy precipitation events shared similar features; the precipitable water anomalies and 850 hPa temperature anomalies were negative along the entire coast and all possessed low-pressure areas northwest of the station that were nearly stationary over the 48 hours of heavy precipitation. For each of these events, heavy precipitation began after an initial frontal passage, was associated with convection in cooler, unstable, post-frontal air, and included the interaction of this flow with coastal terrain (Kreitzberg and Brown 1970; Hobbs et al. 1975; Pike 1987). The mean static stability, $\frac{\partial \theta}{\partial z}$, (Figure 16a, b) over the Pacific Northwest for the three non-AR events that occurred at North Bend, OR (the other two occurred at Newport and Eureka) was considerably less than the stability for the remaining 47 AR-associated events. For the five non-AR extreme precipitation events, much of the higher-elevation precipitation fell as snow, since temperatures were generally about 5-8°C cooler at 850 hPa for these events compared to those associated with ARs (Figure 16c, d). According to U.S. Department of Commerce Storm Data, none of the above non-AR events were associated with flooding.9,10,11 In fact,
one of these storms, 08 January 2005, a top 50 event at Eureka, CA, triggered a heavy
snow advisory for the mountainous terrain above Eureka.\textsuperscript{12} Open-cellular convection can
clearly be seen in the infrared satellite image for this event (Figure 17), a sign of post-frontal
convection, instability, and cooler temperatures.

\textit{b. Atmospheric Rivers without extreme precipitation}

Most wintertime extreme precipitation events along the Pacific Northwest coast are asso-
ciated with AR conditions, but not all ARs result in extreme precipitation near the coast.
Since the majority of atmospheric moisture during AR events is found in the lowest \(\sim 2.5-3.0\)
km of the atmosphere (Browning and Harrold 1970; Browning and Pardoe 1973; Browning
et al. 1974; Peixoto and Oort 1992; Ralph et al. 2005), it is important to understand the
climatological annual cycle of low-level flow and precipitable water on the synoptic scale.

Figure 18 shows 60-year seasonal means of precipitable water and 850 hPa geopotential
heights from the NCEP reanalysis. During the winter months (JFM), the precipitable water
values in the Pacific basin are lowest and increase towards the south, and the westerly 850
hPa flow is at its peak (Figure 18a). During the spring (AMJ), lower-tropospheric high pres-
sure develops over the south-central Pacific and the counter-clockwise flow near the surface
advects moisture northward and eastward out of the tropical western Pacific (Figure 18b).
In the summer (JAS), the low-level air temperature is relatively warm, the average precip-
itable water values in the Pacific basin are highest, the Pacific high extends farthest north,
low-level westerly flow approaching the Northwest is weak, and the mean circulation moves

\textsuperscript{12} U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic
Data Center, Storm Data, 2005, vol. 47.
high precipitable water values north and east (Figure 18c). In the autumn and early winter
(OND), the northeast Pacific high pressure area recedes, the mean maximum low-level flow
increases and moves southward, and the mean precipitable water values decrease (Figure
18d). Interestingly, the highest values of precipitable water (>35 mm) along the West Coast
are found during the warm season when West Coast precipitation is smallest (Neiman et al.
2008a). In contrast, the majority of extreme precipitation events along the West Coast occur
in November, December, and January, when the mean precipitable water values offshore are
much lower. Consistent with the above climatology, most summertime atmospheric rivers
approach the West Coast from the west, in contrast to the southwesterly origin during the
cooler months.

To find days of high precipitable water values but modest precipitation, six-hour NCEP
reanalysis grids during the cool season (October - March) over 1950-2009 were examined for
precipitable water values >35 mm at each of three meridians (125°W, 130°W, and 135°W)
located off of the west coast of the United States (Figure 19). The CPC unified precipita-
tion analysis was used to find daily precipitation totals at every marked grid point (crosses)
along the coast in which there was less than 5 cm of daily precipitation. Only six cases
were found during 1950-2009 with such high precipitable water values and relatively modest
precipitation. Of these, all occurred in October (2), November (3), or December (1). During
the same 60-year period, 34 days with precipitable water values greater than 35 mm and less
than 5 cm of rain along the coast occurred during the warm season (April-September). All
but two occurred in June (7), July (8), August (5), and September (12). Clearly, high pre-

\[^{13}\text{CPC analysis was used instead of observation data to cover the entire coast and grid points were chosen based on proximity to the coast and to avoid higher terrain.}\]
cipitable water values alone are not sufficient for producing extreme precipitation at coastal
sites in the Pacific Northwest. During the summer, a number of elements work against sig-
nificant precipitation. The climatological subtropical high results in a highly stable middle
troposphere, often with an inversion capping a relatively shallow marine layer. Above the
inversion the air is generally quite dry. Low-level flow is far weaker than during winter,
resulting in less orographic uplift and precipitation. Finally, with the summertime configu-
ration of a weakened jet stream and associated disturbances displaced to the north there is
little dynamical support for significant synoptic vertical motions as well as a weak horizontal
moisture flux. The result is little or no precipitation even when vertically integrated water
vapor amounts are high. Neiman et al. (2008a), using satellite-observed integrated water
vapor (IWV), noted large numbers of AR plumes in the summer months along the West
Coast despite those months being the climatologically driest in that region.14

An example of an AR that produced little coastal precipitation occurred on 10 Septem-
ber 2000 (Figure 20). The sea-level pressure anomaly field is dominated by an expansive
subtropical high-pressure anomaly that stretches from north of Hawaii to as far as 50°N and
spans much of the eastern half of the North Pacific Ocean. The moisture plume, which origi-
nates in the western tropical Pacific, is driven north by the Pacific high and upper-level flow
field, extending across the Gulf of Alaska towards the Pacific Northwest. At the time of the
highest precipitable water anomalies along the coast between Forks, WA and Eureka, CA,
and for three days before and after, virtually no rain fell throughout the Pacific Northwest.
In this case and all other summer AR cases, upper-level ridging, weak onshore flow, or a
combination of both, limited upward vertical velocities and precipitation at the coast.

14Neiman et al. (2008a) north domain is north of the Oregon-California border and south of 52.5°N
5. Summary

The Pacific Northwest often experiences extreme precipitation that brings major flooding, landslides, property damage, and loss of life. It is clear from this study and others that atmospheric rivers are responsible for a large majority of extreme events. There is no significant trend in these events over the 60-year period included in this study (Mass et al. 2011) but there is large interannual and decadal variability. This study examines the duration of the region’s extreme precipitation events, the associated synoptic structures, and how their synoptic evolutions differ at various locations along the coast. Aside from a very small subset of events, all wintertime ARs intersecting the coast cause large amounts of precipitation along the coast and farther inland. Although composites of these events at various locations along the coast share similar synoptic features, there are significant differences in the synoptic evolutions leading to these events. Furthermore, non-conventional situations exist in which extreme precipitation can occur without high values of precipitable water or when high moisture values do not produce extreme precipitation.

The top 50 extreme precipitation events in two-day precipitation were identified from 60 years of NCDC daily precipitation data at six Pacific Northwest coastal stations from northern Washington State to northern California: Forks, Astoria, Newport, North Bend, Brookings, and Eureka (Figure 1). Of the 207 dates identified by the top 50 storms at each station, the overwhelming majority occurred during November, December, and January. The 1950s, 1980s, and 1990s experienced more events than the 1960s, 1970s, and 2000s, consistent with previous studies.

NCDC hourly precipitation data at Astoria and Brookings, the two stations with the
most complete 60-year record, were analyzed to determine storm length and the temporal variability of extreme coastal precipitation events. For each location, the associated periods of heavy precipitation ranged from less than one day to greater than three days, with large storm to storm variability. Many of the storms exhibited most of the precipitation in one large spike, while others showed multiple spikes, or relatively steady precipitation over a prolonged period of time.

The 60-year daily precipitation time series for winter months at each station was correlated with the daily average stream flow at nearby unregulated rivers for various time lags. Correlations for 24-hour precipitation were relatively low, most likely due to large events spanning a calendar day. Correlations for 48, 72, and 96 hours were higher, but the correlations were highest at zero- and one-day lags and dropped off considerably for higher lags, suggesting that precipitation beyond 48 hours has already passed through the watershed. This implies that 48 hours is a hydrologically relevant time period to examine heavy precipitation events. The use of a two-day storm definition eliminated the calendar day problem associated with daily precipitation observations and was consistent with time of concentration estimates of less than one day for Pacific Northwest rivers.

Spatial correlations of precipitation show that, on average, precipitation associated with the top 50 two-day precipitation events at all stations did not just affect the coast, but also fell inland along an axis oriented southwest to northeast, with adjacent areas of suppressed precipitation (negative correlations). The width of the enhanced precipitation associated with extreme events was on the order of 200-300 km. Spatial correlations of climatological precipitation did not suggest these structures, indicating more amorphous, larger-scale features and differing precipitation evolutions for non-severe events.
Synoptic composites were made for 500 and 700 hPa geopotential heights, sea-level pressure, 850 hPa temperatures, precipitable water, and integrated moisture flux using the top 50 events for each station at the time of maximum precipitation. The composites at the time of maximum precipitation (time 0) exhibit classic AR signatures and are generally consistent with previous studies (Lackmann and Gyakum 1999; Ralph et al. 2004, 2006; Junker et al. 2008; Neiman et al. 2008a). However, there are differences in the synoptic structures among stations separated by only a few hundred kilometers. The 500 and 700 hPa geopotential height fields showed a deep trough offshore and ridge axis just east of the U.S. West Coast for all stations, but at Forks, the trough stretched deep into the sub-tropics and the upper-level flow was more south-southwesterly over the coast. For stations south of Forks, the trough did not stretch as far to the south and the upper-level flow was southwesterly with the ridge axis farther inland than that of Forks. Additionally, positive temperature anomalies were greater at stations to the north. The precipitable water anomaly composites for each station showed a large positive anomaly oriented southwest to northeast across the station (consistent with spatial correlations in precipitation). The composite precipitable water plume changed from longer, narrower, and originating closer to Hawaii for stations to the north, to shorter, wider, and originating east of Hawaii for stations farther south. Integrated moisture flux anomaly composites closely mirror those of precipitable water and show the extension of the anomalous flux into the subtropical Pacific.

Differences in anomaly composites were not only noted for the time of maximum precipitation, but also for the entire evolution starting three days prior to time 0. It appears that to bring high precipitable water values needed for extreme precipitation to the most northern location required a higher amplitude trough in the eastern Pacific. Negative 500 and 700
hPa geopotential height and sea-level pressure anomalies extended into the central Pacific 72 hours before the event only for the northernmost station, Forks, where the anomalies deepened and moved eastward in subsequent days. All other stations had negative height and sea-level pressure anomalies centered closer to the coast and were relatively stationary in the days prior to the event. Positive temperature anomalies covered the entire coast for stations to the north but were smaller and weaker along the coast for composites to the south. The precipitable water composite evolution showed anomalous moisture in the central Pacific at three days prior to the event for all stations. At Forks, the moisture anomaly consistently strengthened and propagated towards the West Coast in the days leading up to the event, and then remained relatively stationary in the final 24 hours. At all other stations, the precipitable water anomaly initially weakens as it propagates west, and then strengthens at the coast closer to time 0. At two to three days prior to time 0, the upper-level trough in the central Pacific was deeper and extended farther south into the subtropics and tropics for events that impacted Forks. As noted above, this evolution tends to produce a more meridional trough that supports more southerly flow that enhances moisture advection as far north as Washington State. A more southerly flow would also enhance precipitation at Forks, which is surrounded by more south- or southwest-oriented slopes. At the stations to the south, the terrain is oriented north-south and the low-level flow during extreme precipitation events has a more westerly component.

Even though ARs are responsible for the majority of wintertime extreme precipitation events along the West Coast, this study shows there are other ways for extreme precipitation to occur. In three of the southern stations, Newport, North Bend, and Eureka, extreme precipitation sometimes occurred with anomalously low values of precipitable water. These
types of storms occurred five times in the 207 events identified in this study. In each case, the precipitable water values near the station were less than 20 mm, a high-amplitude short-wave trough developed immediately offshore, and negative temperature anomalies covered the entire West Coast. These few events were not represented in the composites due to the dominance of AR-related events and were associated with post-frontal convection in cool, unstable air. The cooler temperatures meant that the majority of precipitation that fell at higher elevations was likely snow, minimizing possible flooding.

Anomalously high moisture values alone are not sufficient to produce heavy precipitation. The highest values in precipitable water near the Pacific Northwest coast occur in the summer (Neiman et al. 2008a) when ocean surface temperatures are relatively warm, the atmosphere is stable, and the winds are weak. This study found only six examples in the cool season (October-March) in which precipitable water values exceeded 35 mm near the northwest U.S Coast and did not produce 24-hour precipitation totals greater than five centimeters. In contrast, 34 of these events occurred during the summer when the jet stream is weaker or displaced much farther north of the Pacific Northwest and the resulting integrated moisture flux is small.

Many questions remain about heavy precipitation along the West Coast. What accounts for the differences in composite evolutions found in this study? To what degree do they reflect the varying topography at each location or the differing evolutions required to bring sufficient moisture and onshore flow to locations at various distance from the subtropical/tropical sources of moisture? How do variation in wind direction, wind speed, and stability of the low-level flow approaching the coast alter the precipitation magnitudes and spatial distributions? What mechanisms control the frequency and intensity of ARs on interannual and decadal
timescales? Future work will be aimed at answering these questions and understanding how extreme precipitation will be affected by a changing climate.

Acknowledgments.

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<table>
<thead>
<tr>
<th></th>
<th>24-hr precip</th>
<th>48-hr precip</th>
<th>72-hr precip</th>
<th>96-hr precip</th>
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<tr>
<td>0 day lag</td>
<td>0.485</td>
<td>0.667</td>
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<td>1 day lag</td>
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<td>3 day lag</td>
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<td>0.460</td>
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Table 2. NCDC Global Historical Climate Network 2-day precipitation totals for the first and 50th ranked storms during the 60-year period 1950-2009 for six stations along the Pacific Northwest coast.

<table>
<thead>
<tr>
<th>Station</th>
<th>#1 Ranked</th>
<th>#50 Ranked</th>
</tr>
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<tbody>
<tr>
<td>Forks, WA</td>
<td>31.0 cm (12.21 in)</td>
<td>15.8 cm (6.23 in)</td>
</tr>
<tr>
<td>Astoria, OR</td>
<td>16.6 cm (6.55 in)</td>
<td>8.81 cm (3.47 in)</td>
</tr>
<tr>
<td>Newport, OR</td>
<td>20.7 cm (8.14 in)</td>
<td>9.37 cm (3.69 in)</td>
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<tr>
<td>North Bend, OR</td>
<td>28.4 cm (11.17 in)</td>
<td>9.07 cm (3.57 in)</td>
</tr>
<tr>
<td>Brookings, OR</td>
<td>24.3 cm (9.55 in)</td>
<td>12.1 cm (4.78 in)</td>
</tr>
<tr>
<td>Eureka, CA</td>
<td>22.4 cm (8.82 in)</td>
<td>7.72 cm (3.04 in)</td>
</tr>
</tbody>
</table>
Table 3. Storm duration statistics at Astoria, OR and Brookings, OR for various percentages of the six-day storm total. Based on hourly data at these locations.

<table>
<thead>
<tr>
<th>% of 6-day</th>
<th>Astoria mean (hrs)</th>
<th>σ (hrs)</th>
<th>Shortest (hrs)</th>
<th>Longest (hrs)</th>
<th>Brookings mean (hrs)</th>
<th>σ (hrs)</th>
<th>Shortest (hrs)</th>
<th>Longest (hrs)</th>
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