Extreme Precipitation over the West Coast of North America:
Is There a Trend?

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Abstract

Heavy precipitation and the resulting flooding are the most serious weather-related hazards over the west coast of North America. This paper analyzes the trends in heavy precipitation for the period 1950 through 2009 by examining the decadal distributions of the top 60, 40, and 20 two-day precipitation events for a collection of stations along the coastal zone of the U.S. and British Columbia, as well as the decadal distribution of maximum daily discharge for unregulated rivers from northern California to Washington State.

During the past 60 years there has been a modest increase in heavy precipitation events over southern and central coastal California, a decline in heavy events from northern California through the central Oregon coast, a substantial increase in major events over Washington, and a modest increase over coastal British Columbia. Most of these trends are not significantly different than zero at the 95% level. The trends in maximum daily discharge of unregulated rivers are consistent with the above pattern, with increasing discharges over the past three decades over Washington and northern Oregon and declines over the remainder of Oregon and northern California. Finally, the above trends in heavy rainfall and daily discharge are compared to the future patterns indicated by general circulation models under various global warming scenarios.
1. Introduction

Flooding due to heavy precipitation is the most serious weather-related threat for the U.S. west coast. Between 1980 and 2008, four flooding events in California, Oregon, and Washington caused losses totaling more than eleven billion dollars. Flooding associated with heavy precipitation led to 25 of 37 presidential disaster declarations since 1955 in Washington State, 14 of 21 presidential declarations in Oregon, and 35 of 192 declarations in California.

A number of articles in the media (e.g., New York Times\(^1\), December 5, 2007) and reports by some non-governmental organizations (e.g., Environment America\(^2\), National Wildlife Federation\(^3\)) have suggested an increasing number of heavy precipitation events over portions of the western U.S. and have proposed that anthropogenic global warming could be the cause. The existence of such increases would have substantial implications for public safety, management of rivers for fisheries and power generation, and other significant societal issues. As described in the next section, several papers have examined the potential for changing precipitation intensity under anthropogenic global warming, with a subset studying recent trends in heavy precipitation and flooding events over the United States.

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\(^{1}\) http://www.nytimes.com/2007/12/05/us/05storms.html?scp=1&sq=extreme%20precipitation&st=cse

\(^{2}\) http://www.environmentamerica.org/uploads/oy/ws/oywshWAwZy-EXPsabQKd4A/When-It-Rains-It-Pours----US---WEB.pdf

This paper reviews the literature regarding trends in heavy precipitation over the U.S. west coast and examines quality controlled precipitation time series from southern California through British Columbia to determine both the nature of the trends at individual locations and how the trends vary spatially. Trends in maximum daily flows from unregulated Pacific Northwest rivers are also considered. These analyses provide context for ongoing and future studies regarding trends in precipitation intensities during the next century under various greenhouse warming scenarios.

2. Previous Studies on Trends in Extreme Precipitation

Changes in precipitation extremes can be produced by alterations in the moisture content of the air or the circulations in which precipitation is embedded. Although some studies (Allen and Ingram 2002, Pall et al 2007) have suggested that extreme precipitation will rise proportionally with water vapor content (roughly 7.5% per °C of warming), other work (O’Gorman and Schneider 2009) has noted that precipitation extremes in the mid-latitudes increase more slowly than total moisture content, with modulation by synoptic forcing and associated vertical motions also being important. Frei et al. (1998) examined the impact of a 2°C warming in a regional climate model over Europe in which relative humidity was kept constant. Light precipitation intensity increased slightly, while the heavier thresholds (greater than 15 mm per day) increased by roughly 15-20% over southern Europe and the Alpine regions.

Several studies have examined trends in heavy precipitation over the U.S., finding a varying and spatially heterogeneous pattern of temporal trends over the West Coast. For example, Kunkel et al (1999) examined extreme (greater than one-year return time)
one-, three-, and seven-day precipitation totals for 1931-1996 using U.S. climate division data and found little trend over coastal California, modest declines over western Oregon, and slight increases over western Washington; none were significant except the declines over western Oregon. The trends for total annual precipitation over the West Coast in the Kunkel study were small and not statistically significant. Kunkel et al. (2003a) compared the anomalies of extreme precipitation for 1895-1905 and 1990-2000 with respect to an extended period (1895-2000). They found small positive anomalies along the West Coast (except for Oregon) for the recent (1990-2000) period, but noted that the positive anomalies were greater for 1895-1905, suggesting the importance of natural variability. Kunkel et al. (2003b) plotted the median value of a set of eight extreme precipitation measures for 1895-2000 (for periods of one, five, and 30 days and one-, five-, and 20-year return periods) and found modest increases over western Washington and northwest Oregon, declines over the central and southern Oregon coastal zones, and little trend over northern coastal California. Karl and Knight (1998) found no trend over the Pacific Northwest between 1910 and 1995 for the proportion of annual precipitation falling in extreme (more than 50.4 mm per day) intensities. In contrast, California and Nevada had a one percent increase in extreme precipitation.

Madsen and Figdor (2007) examined the frequency of one-day precipitation events with a recurrence interval of one year or longer for 1948-2006, using the National Climatic Data Center (NCDC) Cooperative and Summary of the Day data set. They found a modest, statistically significant increase over western Washington, little change over northwest Oregon, a statistically significant decrease over southern Oregon and northern California, and a significant increase over the central and southern California
coastal zones. Zhang et al. (2001) found no significant linear trends in the 90th percentiles of daily precipitation over the Canadian west coast, with generally slight declines over southern British Columbia and small increases over the Queen Charlotte Islands. Pryor (2009), examining precipitation records for 1895-2002, found only a slight upward trend in either the maximum five-day rainfall or the 95th percentile of daily precipitation using a very limited collection of West Coast stations. Rosenberg et al. (2009) evaluated the trends in annual maximum precipitation for a variety of durations (one hour to ten days) for the Spokane, Puget Sound, and Portland areas for 1949-2007. They found a decrease of total annual rainfall over the region, and no evidence of increasing extreme precipitation over the Spokane and Portland areas. Only for the Puget Sound area did the record suggest a statistically significant increase in the frequency of extreme precipitation.

Several studies have used long-term simulations as a tool for examining West Coast precipitation trends. Duliere et al. (2010) examined observed and simulated extreme precipitation trends over the West Coast for 1970-2007. For the annual maximum one-day observed precipitation they found increases over Washington (significant at the 95% level), statistically insignificant decreases over Oregon, and increases over coastal California. The inability of free-running regional climate models (driven by general circulation models) to duplicate this complex pattern suggested to the authors that natural variability and not the influence of anthropogenic global warming was defining West Coast extreme precipitation trends during this period. Tebaldi et al. (2006) analyzed the past-century trends of maximum five-day annual precipitation for nine general circulation models by examining differences in precipitation between 1980-
1999 and 1900-1919. They found modest increases over western Washington and a large upward trend over coastal British Columbia and southeast Alaska. Very little trend was noted over western Oregon and California.

From a hydrological perspective, Linn and Slack (1999), examining the trends of annual streamflow between 1914 and 1993, found no trend over the U.S. west coast except for southern Oregon and northern California, where a significant downward trend was observed.

The above studies are characterized by considerable differences in the magnitude and sign of extreme precipitation trends, the periods and extreme precipitation measures considered, and the spatial variability of the trends. Nevertheless, many of these studies had elements in common. Specifically, many indicated an increase of extreme precipitation over western Washington, a decline in western Oregon and northern California, and modest increases in the remainder of coastal California. In order to appraise the significance of this pattern and to carefully study the nature of extreme precipitation trends over the west coast of North America, the present study examines the nature of extreme precipitation over the region for the period 1950 through 2009 using high quality station data and the discharge rates of major, unregulated river systems.

3. Analysis of Trends in Precipitation

This study makes use of precipitation records from the U.S. Historical Climate Network (USHCN) and the Canadian Daily Climate Data (CDCD) dataset. As shown in Figure 1, a line of evenly spaced coastal or near-coastal stations was selected from southern California through British Columbia. Coastal stations are particularly useful for
evaluating West Coast precipitation trends. First, the lack of upstream terrain is a substantial benefit since it removes the effects of rainshadowing and other wind-dependent influences on precipitation. Second, coastal stations receive little snow, and snow is often poorly measured, particularly when heavy. Finally, coastal rainfall is highly correlated with precipitation over downstream terrain, as demonstrated by correlations between coastal stations and the NOAA Unified rainfall analysis (not shown).

Each station was carefully quality controlled beginning with gross error checks. Since accumulated precipitation is sometimes provided after a period without reports (generally due to the unavailability of manual observations), large precipitation values after multi-day periods of zero or missing precipitation were not used in this study. Each of the stations used had at least 95% availability of calendar-day precipitation totals for 1950-2009, the period of study of this work.

At each station, the extreme values of two-day precipitation totals were examined. There are several reasons for selecting this period. For moderate to large watersheds of the mountainous west, precipitation over roughly one to two days has been suggested to be the most hydrologically relevant for major flooding events (Dennis Lettenmaier, Jessica Lundquist, University of Washington, Department of Civil Engineering, private communications, 2010) and this time scale approximately matches the period of heavy precipitation for western U.S. major precipitation occurrences associated with major atmospheric river events (Larry Schick, U.S. Army Corps of Engineers, Northwest region, lead forecaster, private communication, 2010). Secondly, as part of this study the daily precipitation at coastal sites was correlated with the streamflow for nearby unregulated rivers. It was found that the highest correlations occurred at one or two day
lags, indicating that precipitation falling in nearby watersheds is through the system within two days. Finally, extreme two-day precipitation totals match well with documented western U.S. flooding events.

Figure 2 presents histograms of the number of events per decade for the top 20, 40, and 60 events for a line of coastal or near coastal stations from Chula Vista in southern California, to Langara, British Columbia, on the northernmost portion of the Queen Charlotte Islands. The use of top events allows an easy comparison of locations with substantially different amounts of precipitation, and the decadal distribution of these events provides information on trends. Best-fit (least squares) trend lines for the top 20, 40, and 60 events at each site are also shown. The statistical significance of the trend lines will be examined later in the discussion of Figures 3 and 4. Shorter averaging periods were also evaluated (e.g., five years); the resulting plots showed similar trends and more temporal variability.

There was considerable variability in the trends over southern California for the top 60 events: some (Chula Vista, Santa Barbara, San Luis Obispo) had increasing trends, while Newport Beach had a decline. For the top 20 and 40 storms the trends were relatively small, with largest upward trend at Santa Barbara. Little trend was evident over central California (Santa Cruz), while observing sites over northern California (Fort Bragg, Eureka) evinced declining trends in all three classes of top storms. Tillamook, on the central Oregon coast, appears to be a transition site to a different trend regime, with increases in all categories. The decade of the 1990s stands out with a large number of events. The central and northern Washington coast locations (Aberdeen and Forks) had an upward trend in all three categories of heavy precipitation (only a slight rise for the top
20 at Forks), with the 1990s again being the most extreme decade. Over Vancouver Island (Pachina Point and Port Hardy) there is an upward trend for the top 20 and 40 categories (very slight at Port Hardy), with a substantial upward top 60 trend for Port Hardy and a decline for the top 60 at Pachena Point. At Sandspit on the Queen Charlotte Islands there is an increasing trend for the top 60 and 40 categories and a decline for the top 20. Finally, at Langara Island on the northern part of the domain, there is very little trend for the top 60 and 20 categories and only a slight rise for the top 40.

To better appraise the existence and significance of trends in extreme precipitation, the number of top 60 and 20 precipitation events at individual stations and for two-degree (latitude) bands are presented in Figures 3 and 4. The significance of the trends was analyzed using a formula similar to that used by Casola et al. (2009) for determining the 95% confidence intervals of the trends, utilizing a two-sided Student’s t test. Specifically, if $\beta$ is the slope of the least squares best-fit trend line and $N$ is the number of decades (in this case, six), the slopes at the 95% confidence level would range between $\beta + \alpha$ and $\beta - \alpha$, where

$$\alpha = t_{N-2} \sqrt{\frac{\sum_{i=1}^{N} \epsilon_i^2}{\sum_{i=1}^{N} (x_i - \bar{x})^2}}$$  \hspace{1cm} (1)

$t_{N-2}$ is the 95th percentile value from the $t$ distribution, and the residual between the decadal and trend-line values is $\epsilon_i$. This formula is based on the Student’s $t$-distribution, and assumes that the non-trend variability is primarily Gaussian white noise. Plotting the

\[ A \text{ derivation of this formula can be found at} \hspace{1cm} \text{http://en.wikipedia.org/wiki/Simple_linear_regression} \]
residuals confirmed their nearly Gaussian characteristics.

Examining the top 60 events at individual stations along the west coast of North America (Figure 3a), finds a modest increasing trend (0-50%) over southern California for most stations, and a decreasing trend over northern California and south-central coastal Oregon north of approximately 39°N. The decline at Eureka (41°N) is large and highly significant, while for the other California locations the trends are generally not different than zero at the 95% confidence level. In northern Oregon the trend becomes positive and by the central Washington coast (Aberdeen, 47°N), the increase is large, but not significantly different than zero at the 95% level. Moving northward into British Columbia (north of 48.5°N) the 60-year trends are generally increasing, with none being different than zero at the 95% level. Averaging the station data over two-degree bands and then computing the trends (Figure 3b) produces a smoother latitudinal trend variation with less amplitude and a less significance. A slight increasing trend is evident over southern California, transitioning to a decline in the northern portion of the state. A minimal trend in Oregon becomes an increase over Washington, and then a smaller increase over British Columbia. None of these trends are different than zero at the 95% significance level.

The results for the top 20 events (Figure 4) show far more variability and less significance in the trends. Examining individual stations, there is generally no consistent trend over southern and central California and a declining trend over northern California and southern Oregon, with none of the latter being different than zero at the 95% significance level. Increasingly heavy precipitation is found over northern Oregon, Washington, and southern British Columbia, with the trends over Washington being
highly significant. Finally, there is very little trend in the most extreme precipitation amounts over the remainder of coastal British Columbia. Averaging the station data over two-degree bands (Figure 4b), produces similar, but attenuated, variability in latitude: little trend over southern California, a decline over northern California that reaches roughly the 90% significance level, a slight decline over Oregon and a larger increase over Washington and southern British Columbia that are significantly different from zero at the 95% level. Farther north there are non-significant increases.

A complementary approach is to evaluate the trends of maximum annual two-day precipitation for each site. The results of such analysis are shown in Figure 5, which presents the linear least-squares best fit trend for maximum annual two-day precipitation for 1950-2009 as well as the 95% confidence interval calculated using equation (1) above. The results are consistent with trends calculated for the top 20 or 60 events based on decadal frequencies. Southern and central California coastal trends are generally small with substantial variability, while over northern California the trends are consistent and negative (decreasingly by roughly 0.3 mm per year or 18 mm over the 60-year period). Over Oregon the trends transition from negative over the southern coast to positive over the northwestern portion of the state. None of the trends over California or Oregon are significantly different from zero at the 95% level, although the decline at Fort Bragg (39°N) comes close. The upward trend on the Washington coast (Aberdeen) is both large (increase of 66 mm over 60 years) and highly significant. This upward trend declines in amplitude and significance over far northern Washington and British Columbia.
4. **Trends in Discharge Rates of Unregulated Rivers**

Trends in heavy precipitation should be reflected in river discharge. Figure 6 shows the positions of 14 unregulated river gauges. Average daily streamflow at each river for the period 1950-2009 was used in this analysis. The decadal variation of the top 60 and 20 daily discharges for unregulated coastal or near-coastal rivers are plotted in Figure 7 for six rivers north of 45°N (northern Oregon and Washington) and eight rivers south of that latitude (northern California and south/central Oregon).

A very different decadal variation is evident in the two latitude bands for both the top 60 and 20 events. For the top 60 events, there is a general upward trend in the frequency of the highest discharges north of 45°N, with peak frequencies in the 1990s for all the rivers except the Quinault. In contrast, south of 45°N, the peak in the 1990s is absent and the maximum discharges are found during the first three decades, with a distinct and large decline in the 1980s that is maintained through the 1990s and 2000s. For the top 20 events and north of 45°N, the peak in the 1990s is dominant; without this decade little trend is evident. South of 45°N there is dramatic decline in the number of major events in the latter three decades. The spatial pattern in maximum river discharge trends parallels that found for heavy precipitation in this work and others, with increases in northern Oregon and Washington and declines in most of Oregon and northern California.

5. **Discussion and Summary**

This study has examined trends in extreme two-day precipitation along the west coast of the U.S. and British Columbia for 1950-2009, as well as maximum daily stream
flow over the Pacific Northwest for the same period. The extreme two-day precipitation and maximum daily stream flows suggest a consistent pattern for the decadal trends over the west coast of North America, a pattern that was also suggested in earlier work for other periods. Specifically, examining the top 20, 40 and 60 precipitation events over the 60-year period using high-quality observing sites along the coastal zone of western North America suggests a small increasing trend over southern California, transitioning to a statistically significant decline over northern California and south-central coastal Oregon. Over northern Oregon extreme precipitation frequency is increasing, with large, highly significant increases over the Washington coast. Farther north, over coastal British Columbia, extreme precipitation is generally increasing, but with smaller amplitude and less significance. Examining West Coast coastal trends in extreme daily streamflow reveals a similar geographical pattern with increasing extreme streamflow over Washington and northern Oregon and declining trends for the remainder of Oregon and northern California. Thus, an important finding of this work is that heavy precipitation trends over the past 60 years vary in a coherent way along the west coast of North America.

Intriguingly, the geographical variation in the trends of heavy West Coast precipitation events parallels the spatial variation in the trends of extreme winds associated with deep synoptic low-pressure systems. For example, Mass and Dotson (2010) showed that over the past 60 years, major cyclone-related windstorms have become less frequent over Oregon and more common over Washington State. Are there underlying synoptic changes producing the substantial decadal modulation of intense precipitation and wind events?
It is of interest to compare the above geophysical patterns of trends in extreme West Coast precipitation to those predicted over the next century by general circulation model forecasts and regional climate models. Chen et al. (2003) examined the impacts of doubling CO$_2$ using the MM5 and RegCM2 regional models for downscaling a global CCSM GCM simulation. They found an increase in average precipitation over central California and a decline over the Pacific Northwest, a pattern quite different than the one described above. Kim (2005) compared the extreme precipitation produced by the MAS regional model downscaled from the HadCM2 global circulation model for two periods: 1990-2000 and 2040-2049. Examining the change in frequency of days exceeding 50.8 and 101.6 mm per day, he found the largest increases over northern California and Oregon, with little trend in the most extreme precipitation over Washington and southern California. Again, a pattern quite distinct from that observed since 1950. Tebaldi et al. (2006) examined several measures of extreme precipitation from an ensemble of nine general circulation models using a range of emission scenarios. They found a general increase of extreme precipitation over Oregon, Washington, and British Columbia, with the magnitude of the positive trend increasing to the north, while decreasing or constant intensity was predicted over central and southern California; a pattern closer, but not identical to, that observed over the past 60 years. Duffy et al. (2006) analyzed the precipitation produced over the western U.S. by four regional climate models nested within two global ocean-atmosphere climate models, finding that the spatial distributions of precipitation vary substantially among the regional climate models.

Considering the large variability in precipitation trends among the various general circulation models in the above studies and their associated regional climate models, and
the differences between the simulated trend distributions and the observed trend patterns found in this study and others, it is unclear whether anthropogenic global warming is the source of past spatial patterns of extreme precipitation trends along the west coast of North America. A similar conclusion based on retrospective climate simulations was made by Duliere et al. (2010), who suggested that the coherent observed patterns in extreme precipitation trends were associated with natural variability.

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References


Dulière, V., Zhang, Y. and E. Salathé, 2010: Changes in 20th century extreme temperature and precipitation over the western United States from regional climate model simulations and observations. Submitted to *Climatic Change*


Kim, J., 2005: A projection of the effects of the climate change induced by increased CO2 on extreme hydrologic events in the western U.S. *Climatic Change*, 68, 153-168


Figure Captions

Figure 1: Precipitation gauge locations analyzed in this paper. Up and down arrows indicate increasing or decreasing 60-year trends.

Figure 2: The number of events per decade versus time for the top 20 (blue), 40 (green), and 60 (red) events over the 60-year period. The least squares best-fit linear trends are also shown for the three categories.

Figure 3: Sixty year trends for the top 60 events for all stations (top) and for averages of the stations over 2° latitude bands (bottom). The trends are given in percent change over the 60-year period. The vertical dotted lines indicate the state boundaries and the brackets indicate the 95% interval derived from using formula (1).

Figure 4: Sixty year trends for the top 20 events for all stations (top) and for averages of the stations over 2° latitude bands (bottom). The trends are given in percent change over the 60-yr period. The vertical dotted lines indicate the state boundaries and the brackets indicate the 95% interval derived from using formula (1).

Figure 5: Sixty year trends (mm per year) for the maximum two-day precipitation for coastal locations from southern California to British Columbia. The vertical dotted lines indicate the state boundaries and the brackets indicate the 95% confidence interval derived from using formula (1).
Figure 6: Locations of gauges on unregulated rivers used in this study. Up arrows indicate increasing trends and down arrows signify decreasing trends in maximum daily discharge from 1950-2009.

Figure 7: Decadal variation of the top 20 (left) and 60 (right) average daily discharges for 1950-2009 for unregulated rivers north and south of 45°N latitude.
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Figure 3: Sixty-year trends for the top 60 events for all stations (a) and for averages of the stations over 2° latitude bands (b). The trends are given in percent change relative to the mean over the 60-year period. The vertical dotted lines indicate the state boundaries and the brackets indicate the 95% interval derived from using formula (1).
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