Impacts of Climate Variability and Climate Change on Transportation Systems and Infrastructure in the Pacific Northwest

Flooding on Interstate 5 near Chehalis, WA on Jan 8, 2009. (Source: SeattlePI.com)

Alan F. Hamlet

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1. EXECUTIVE SUMMARY

Climate variability and projected regional climate change due to increasing greenhouse gas concentrations have important implications for transportation systems and infrastructure in the Pacific Northwest (PNW). 20th century climate variability in the PNW is characterized by inter-decadal and inter-annual variations in climate associated with the Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO) respectively, and by other factors such as the observed increases in the variance of cool season (Oct-Mar) precipitation since about 1975. Such variations in climate have been shown to affect hydrologic extremes (e.g. river flooding and stormwater runoff), which in turn have important implications for the management and design of transportation systems. These extremes have caused roadway inundation, damage to infrastructure due to erosion, scour, or debris, and roadway closures due to avalanche or mudslides. Additionally, climate variability may influence design of drainage and stormwater management systems, snow removal, timing of seasonal road closures, and a wide range of public safety issues addressed under the Federal Emergency Management System. Inter-annual climate variability also has important implications for sea level as well, with warm ENSO events typically bringing sea levels about 30 cm (12 in) higher than normal and larger amplitude waves. These factors are important in some low-lying coastal areas. Some aspects of PNW climate variability (e.g. ENSO) are predictable with relatively long lead times, which may allow for improved allocation of resources for maintenance or new construction, or improved information services related to public safety.

Global climate change is projected to bring warmer temperatures and changes in the seasonality of precipitation in the PNW. These changes are projected to lead to increased extreme high temperatures and decreased the extreme low temperatures, wetter conditions in winter, spring, and fall, and drier summers. These changes are also projected to decrease mountain snowpack (especially at moderate elevations) and the frequency of low elevation snow storms. Hydrologic extremes such as flooding are projected to increase or decrease in different ways in different parts of the PNW, depending in part on variations in mid-winter temperatures and the spatial distribution of precipitation change. Loss of snowpack may decrease avalanche risks at moderate elevations (such as mountain passes) while raising the risk of landslides, debris flows, and scour due to an increase in exposed soils. Uncertain changes in precipitation extremes may affect the performance of stormwater systems, the frequency of infrastructure damage, and public safety. Sea level rise (estimates for which are rapidly changing with increasing knowledge of land ice losses) is projected to threaten coastal transportation infrastructure such as roads in low-lying areas, roadways on dikes and levies, or in coastal areas subject to beach erosion. Sea level rise may also create drainage problems in low gradient areas.

Projected rapid changes in climate in the 21st century raise the concern that traditional design processes that assume a stationary climate, or "replace-in-kind" policies currently part of some federal maintenance and funding programs (see e.g. http://www.fhwa.dot.gov/reports/erm/ermchap2.cfm), may become less effective over time, leading to potentially increased rates of infrastructure failure if alternative approaches are not developed. Several alternative strategies provide opportunities to incorporate climate change into more robust transportation plans, designs, and operations. Design standards can be based on modeling projections rather than retrospective data, or may use monitoring to modify current practices as problems become apparent. Infrastructure with a relatively short life cycles, for example, may be able to rely primarily on monitoring to guide updated design standards, whereas infrastructure with a relatively long life cycle or high replacement cost may require greater margins of safety in the design process reflecting future conditions and/or more flexible designs that permit changes to be made if conditions outside the original design specifications are encountered (Waskum 2010). Flexible designs, such as expandable sea walls or levies for flood prevention, can be modularly enlarged or strengthened to cope with more extreme conditions without investing at the outset in expensive infrastructure to deal with the worst case. Such approaches are also well aligned with engineering economics that increase the future value of money (i.e. postponing investment always reduces present costs). Another strategy is to simply increase margins of safety across the board to account for the general direction of change. As vulnerable locations or structures are identified, additional attention can be focused on other elements of the design process in these areas in an attempt to increase the robustness of the design. This suite of strategies will need to consider the regulatory framework that guides designs and operations and seek efforts to simplify updates and approval processes while remaining responsive to changing conditions. Careful integration of science and engineering will be essential to coping with changing risk to the region's transportation system in the 21st century.

2. INTRODUCTION

This white paper was motivated by the need to better understand the many potential impact pathways for transportation systems and infrastructure associated with climate variability and climate change in the Pacific Northwest (PNW). Impact pathways are the means by which climate change will determine outcomes in sectors such as transportation. These outcomes may be primary (e.g. pavement softening because of warm temperature) or secondary (e.g. increased precipitation leading to flooding that washes out a road). Interest in these areas of research is related in part to an apparent increase in the severity of extreme hydrologic events in the last several decades. In many areas of western WA, for example, there has been an apparent shift towards higher extreme river flows (Hamlet et al. 2007; Neiman et al. 2011), and in many cases the most extreme four or five flooding events have all occurred in the last 20 years or so. Figure 1, for example, shows the historical record of peak flow for the Skykomish River at Goldbar, WA. Note that the three largest events have all occurred since about 1980, and that the largest (and most recent) event is about 30% higher than the largest previous event. Two recent events in the Chehalis River floodplain have put many transportation managers and planners on alert. These back-to-back extreme events (in Dec, 2007 and Jan, 2009 respectively) put Interstate 5 more than 10 ft underwater for multiple days in each event, costing the region hundreds of millions of dollars in lost transportation-related revenue in each event. Most rivers in western WA are experiencing the same changes in extreme high flows, which supports the argument that the changes are related to a shift in climate rather than changes in land use or stormwater management practices.

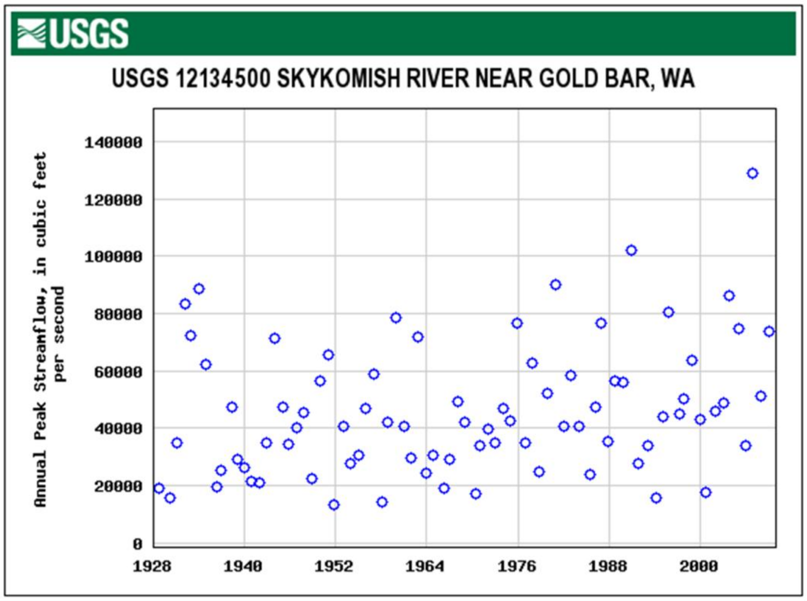


Figure 1. Peak flow record for the Skykomish River near Gold Bar, WA (1928-2009).

These kinds of observations raise many important questions about the nature of these changing extremes. Are these changes unique to the PNW? Are they caused primarily by changes in extreme precipitation or are other factors involved? Are they expressions of natural variability, or are they related to more systematic changes in climate associated with global climate change or other human-caused factors? Are there other kinds of changes taking place that we should be aware of? What should we expect for the future?

Projections of a non-stationary and rapidly evolving climate system also raise many important questions about the way we currently manage and think about transportation systems and their relationship to climate (Jake et al. *in review*, Milly et al. 2008, Matter 2010). A non-stationary climate implies that forecasting of climate cannot rely on the assumption that past statistical properties of climate will be the same in the future. If the climate is changing, should the way in which we plan, design, manage, and prepare for emergencies in our transportation systems also change? If so, what are the key areas of concern associated with the management of our transportation system in the face of a historically changeable, and apparently systematically changing, environment?

3. OVERVIEW OF PACIFIC NORTHWEST CLIMATE

3.1 CLIMATE VARIABILITY

Climate in the Pacific Northwest (PNW) has varied substantially on centennial (century-to-century), decadal (decade-to-decade), and inter-annual (year-to-year) time scales in the 19th and 20th centuries (Mote et al. 2003). Figure 2 shows a long time series of annual naturalized (i.e. observed flows with water management effects removed) flow in the Columbia River at The Dalles OR from 1858-1999. Annual flow in the Columbia River is strongly correlated ($R^2 = 0.82$) with cool season (Oct-March) precipitation over the entire PNW, so these flow records are a very useful proxy for cool season precipitation variability for the region as a whole. Although trends in cool season precipitation have been relatively small in the 20th century, the 19th century was much wetter than the 20th century as a whole. The two wettest years in the 20th century (water year 1974 and 1997) were matched or exceeded five times in the last 40 years of the 19th century according to these proxy records. Water year 1894 (Oct, 1893-Sept 1994) produced observed peak flows at The Dalles, OR that were almost 50% higher than naturalized flows in the most extreme years in the 20th century (~ 800,000 cfs in 1974 and 1997 v.s. ~ 1.2 million cfs in 1894).

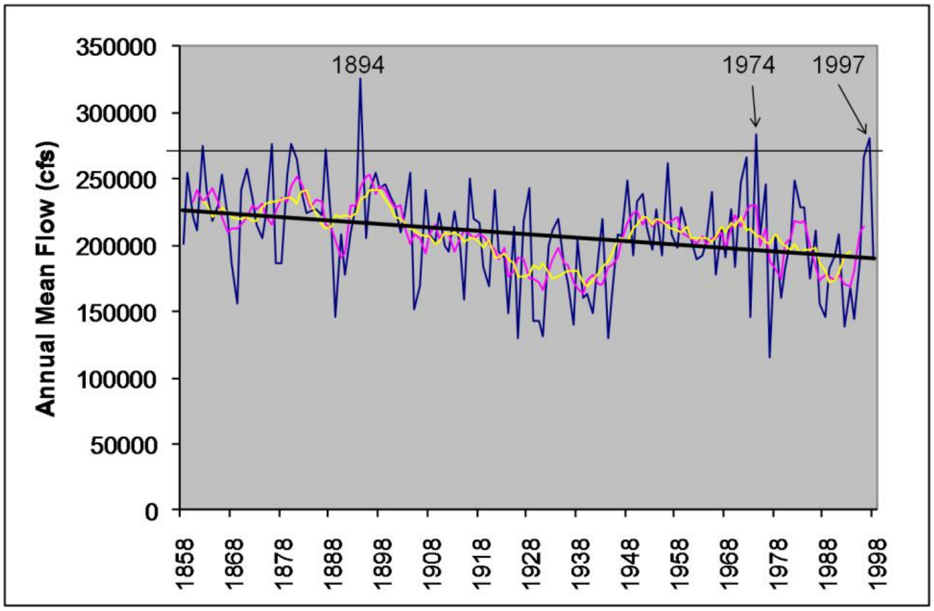


Figure 2. Naturalized annual flow (i.e. observed flows with water management effects removed) in the Columbia River at The Dalles, OR from water year 1858-1998. Flows from water years 1858-1877 are reconstructed using regression from estimates of peak stage from railroad records (R^2=0.82) . Flows from 1878-1998 are naturalized data derived from daily USGS gage records. The heavy dark line shows the linear trend line from 1858-1998. The pink and yellow lines are smoothed curves from 5-year and 10-year moving averages, respectively.

Effects of ENSO and PDO on Streamflow

Decadal and inter-annual variations in climate have also played an important role in determining 20th century climate variations. Figure 3 shows decadal and inter-annual patterns of warm season (April-September) naturalized flow in the Columbia River associated with the Pacific Decadal Oscillation (Mantua et al. 1997), and with the El Niño Southern Oscillation (ENSO) (Battisti and Sarachik 1995). Like annual flow, warm season flow in the Columbia River is strongly controlled by cool season precipitation over the region as a whole. Decadal patterns associated with the PDO (which persists in predominantly warm or cool phase on the order of 25 years) explains the shifting mean from decade to decade, whereas ENSO variations (warm, neutral, or cool) explain the year-to-year variations around these changing mean conditions. In each “bin” representing predominantly warm or cool phase PDO conditions, warm ENSO (El Niño) events are typically confined to the lower two thirds of the probability distribution, whereas cool ENSO (La Niña) events are typically in the upper two thirds of the probability distribution (Hamlet and Lettenmaier 1999; Mote et al. 2003). ENSO neutral years (neither warm nor cool) vary around the average conditions with above average and below average conditions about equally likely. It is important to note that decadal shifts in climate can occur very rapidly (over a year or two) and then persist for multiple decades. Such behavior has been described as a “regime shift” in climate (Mantua et al. 1997; Hare and Mantua 2000). In 1976-1977, for example, there was a very pronounced and rapid shift in climate from predominantly cool and wet conditions from about 1947-1976 (cool phase PDO) to relatively warm and dry conditions from 1977 to at least 1995 (warm phase PDO) (Hare and Mantua 2000).

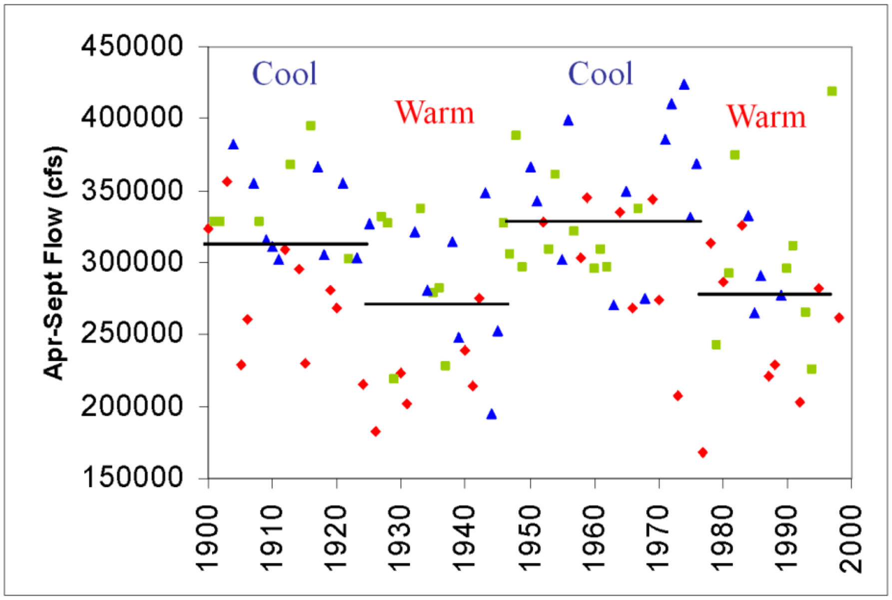
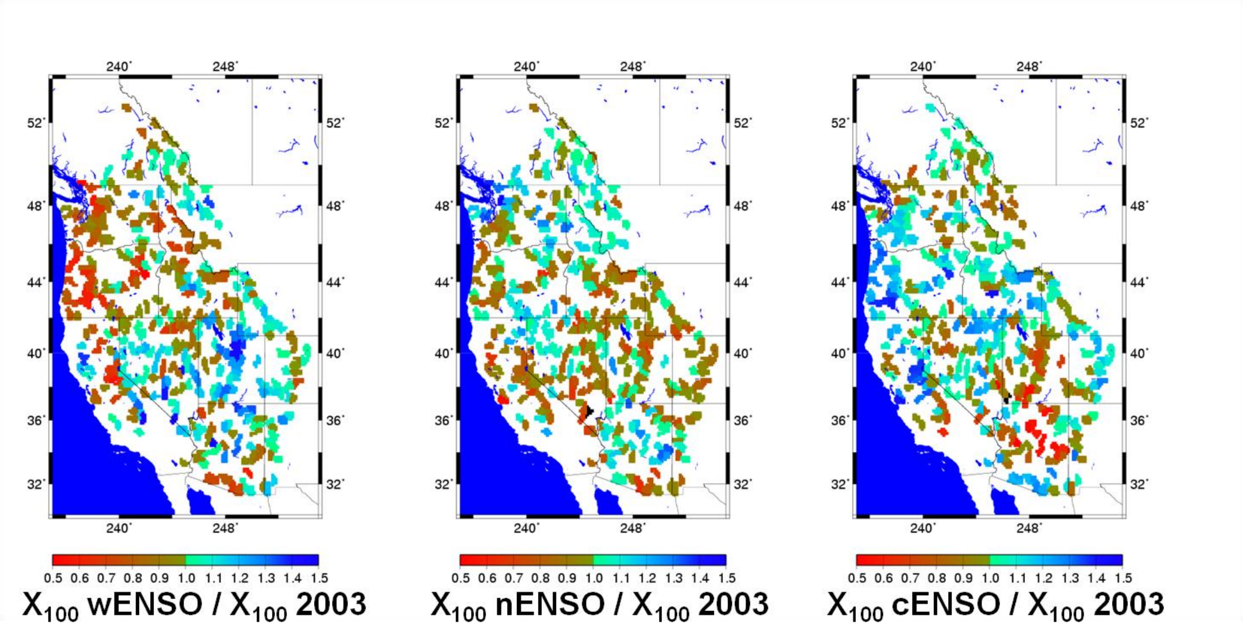


Figure 3. Naturalized April-September Average flow in the Columbia River at The Dalles, OR from 1900-1999. Cool and warm PDO epochs are identified at the top of the figure, and the long-term mean for each epoch is shown by the black horizontal lines. Red diamonds are warm ENSO years, blue triangles are cool ENSO years, and green squares are ENSO neutral years.

Effects to Hydrologic Extremes

Hydrologic extremes have been shown to exhibit "regime like" behavior associated with decadal climate variability (Kiem et al. 2001; Hamlet and Lettenmaier 2007), and in the PNW historical PDO and ENSO variations explain variations hydrologic extremes through the 20th century. Hamlet and Lettenmaier (2007), for example, showed that simulated flood risks in the 20th century varied with ENSO and PDO, with the highest historical flood risks occurring in ENSO neutral and cool ENSO years (Figure 4). Decadal variations in climate were also shown to affect flood risk, with higher flood risks in the PNW in cool PDO periods and lower flood risks in warm PDO periods.



X_{100} wENSO / X_{100} 2003 X_{100} nENSO / X_{100} 2003 X_{100} cENSO / X_{100} 2003

Figure 4. Flood risks in the western U.S. for warm, neutral, and cool ENSO years shown as a ratio of the 100-year event in each ENSO category compared to the 100-year event for all years. (Temperatures have been detrended to reflect late 20th century conditions.). Source: Hamlet and Lettenmaier (2007).

Changing Cool Season Precipitation Variability

Changes in the variability of cool season precipitation have also been readily apparent in the 20th century. Since about 1975, statistically significant shifts in the variance of cool season precipitation have been observed over the entire western U.S. (Figure 5), with corresponding increases in flood risk in many areas (Hamlet and Lettenmaier, 2007).

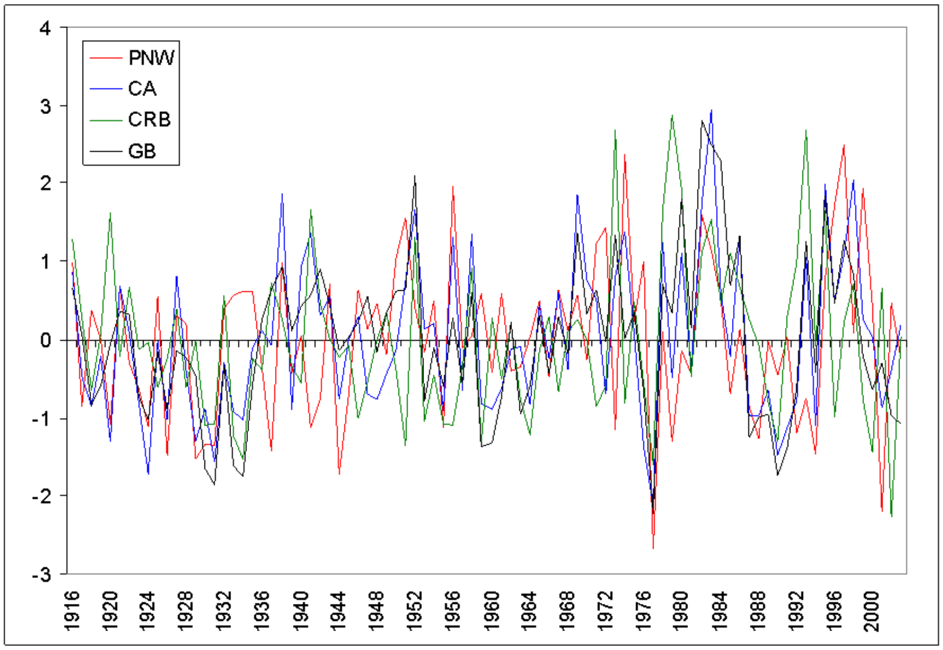


Figure 5. Standardized anomalies (change from the long term mean divided by the standard deviation) of cool season (Oct. – March) precipitation averaged over four large regions in the western U.S. (PNW -Pacific Northwest, CA - California, CRB - Colorado River Basin, and GB - Great Basin, respectively) from 1916-2003 showing the dramatic expansion in the variance of cool season precipitation since about 1975 and the increasing covariance between regions. Source: Hamlet and Lettenmaier (2007).

Effects to Temperature

Although, in isolation, temperature is probably not one of the most important variables related to transportation impacts in the PNW, 20th century variations in temperatures in the PNW are also related to observed patterns of ENSO and PDO. In warm ENSO years, for example, cool season temperatures are on the order of 1° C (1.8° F) warmer than normal on average (Mote et al. 2003). Summer temperatures in the PNW, and high temperature extremes, however, are not well correlated with ENSO. Figure 6, however, shows that long-term trends in temperature (related to global climate change and other factors) have had a significant influence on observed 20th century temperatures (as discussed in subsequent sections).

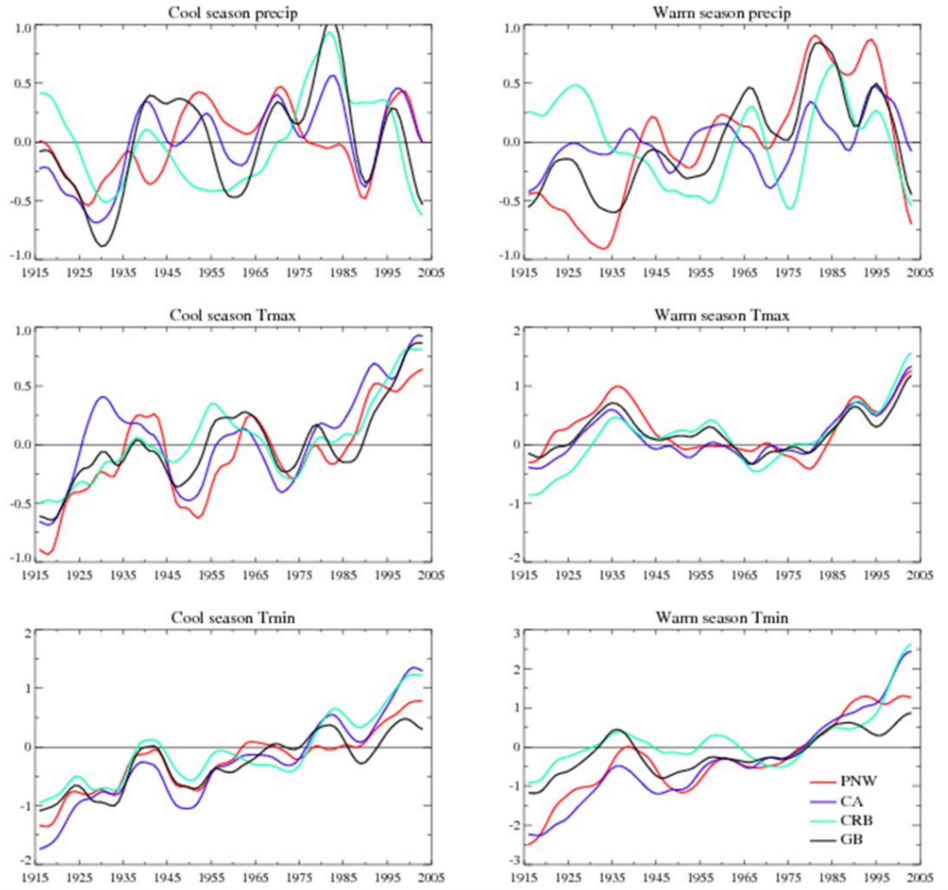


Figure 6. A temporally smoothed 20th century time series (1915-2003) of regionally averaged precipitation, maximum temperature, and minimum temperature for cool season (Oct-March) and warm season (April-Sept) over the western U.S. (Pacific Northwest, California, Colorado River Basin, and Great Basin) expressed as standardized anomalies (number of standard deviations from the mean). Source: Hamlet et al. (2007).

Other hydrologic variables that are affected by temperature and precipitation are also significantly affected by climate variability. One of the most important of these in the context of transportation impacts is snowfall and snowpack. Figure 7 shows the variations in April 1 snowpack expressed as anomalies (difference from normal) in snow water equivalent (SWE, or the total water content of the snowpack) for warm ENSO and cool ENSO years. Snowpack in the relatively warm areas west of the Cascades, for example, is unusually sensitive to ENSO variations from year to year since both temperature and precipitation are important drivers of inter-annual snowpack variability. Anomalies (differences from normal) in November to March snowfall from station observations show similar geographic patterns (Figure 8, NOAA 2005; Knowles et al. 2006).

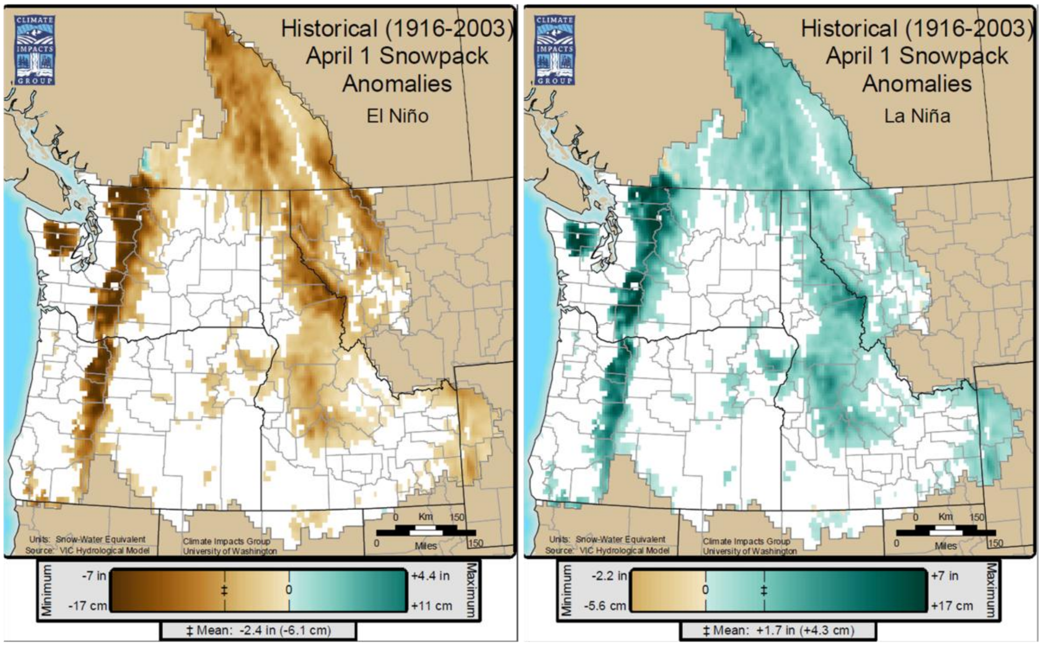


Figure 7. Simulated average April 1 snow water equivalent over the PNW for warm ENSO (left) and cool ENSO (right) composites. Data from 1916-2003. Source: CIG (2011).

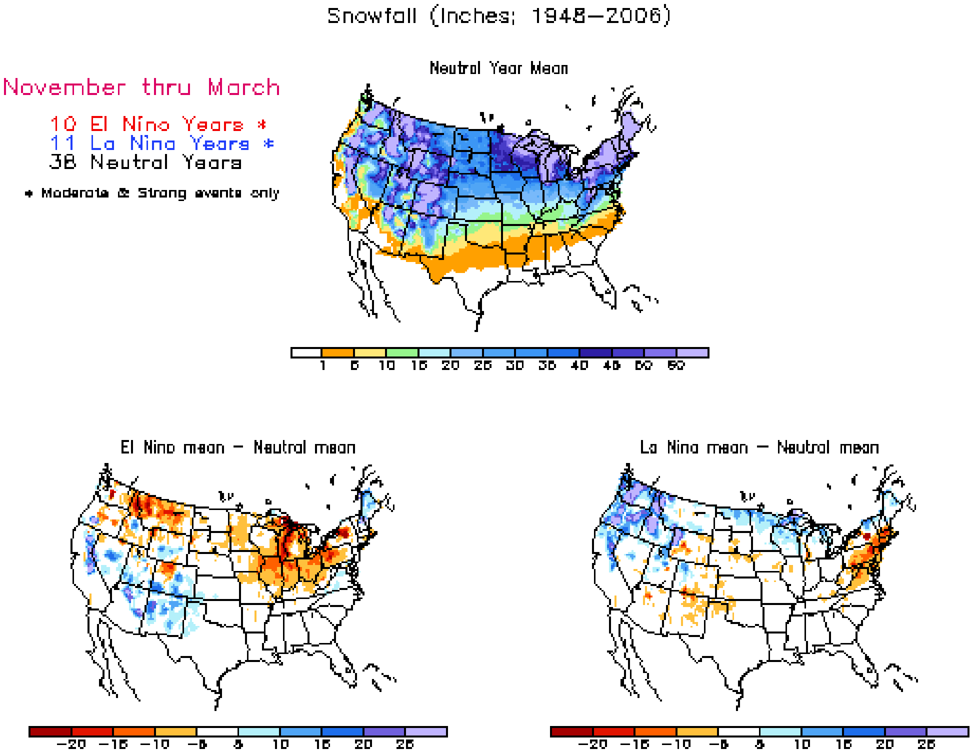


Figure 8. Total snowfall (inches) from low and moderated elevation station observations in ENSO Neutral years (top) and anomalies for warm (lower left) and cool (lower right) ENSO events. Source: NOAA (2005).

Effects to Local Sea Level

Local sea level is also strongly influenced by ENSO variability in the PNW. In warm ENSO events, sea level in Puget Sound near Port Townsend, WA is typically about 10 cm (~4 inches) higher than normal on average, and for the strongest warm ENSO events sea level in Puget Sound is almost 25 cm (~10 inches) higher than normal (Figure 9). In the relatively strong warm ENSO event of 2009-2010, so called “king tides” (king tides occur when the Earth, moon and sun are aligned in such a way that the tidal cycle has an unusually high amplitude) produced water levels in Puget Sound that were on the order of 2 ft higher than normal (Figure 10). Because of elevated sea level and changes in wave intensity, increased coastal erosion and storm damage (and human responses to these impacts such as coastal armoring) are typically seen during (and immediately following) warm ENSO years. These historical variations in sea level provide some important historical context for vulnerability to increased sea level due to global climate change projected in the 21st century. In particular these historical impacts are useful for identifying transportation infrastructure that is vulnerable to sea level rise. There are, however, also important differences between historical impacts and those that would be projected for climate change. In particular, elevated sea levels during warm ENSO events are typically paired with reduced flood risks (as above). In the case of global warming impacts to sea level, elevated sea levels will also be paired with cool ENSO events and higher risks of extreme storms. Thus, in the near coastal environment near rivers (which are affected by both sea level and river flooding), impacts in historical warm ENSO events may be less severe than those associated with a comparable level of sea level due to global climate change.

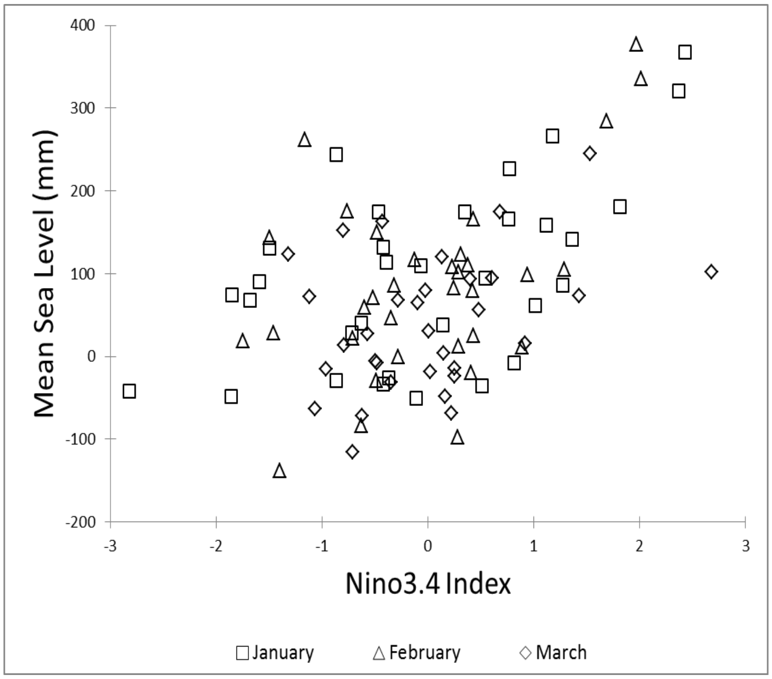


Figure 9. Scatter plot of mean sea level (mm) for Port Townsend, WA and the mean Nino3.4 Index (a numerical measure of ENSO phase and strength) for December, January, and February from 1/1972-12/2009.

Figure 10. Effects of a "King Tide" at the Nisqually Wildlife Refuge in Sound Puget Sound on Feb 2, 2010 (photo by Russ McMillan). Source: WDOE (2011).

Windstorms

Extreme wind storms, and the downed trees and power outages that result, are a significant threat to public safety in the transportation sector. Bridge closures and other emergency management procedures may also impact the transportation system during extreme events. Although relatively little data is available to support a comprehensive analysis over long time scales, currently there is currently little to suggest any robust relationships between extreme wind storms and the patterns of climate variability associated with PDO and ENSO discussed above.

3.2 CLIMATE CHANGE PROJECTIONS

Observed Climate Change in the 20th Century

Detection and attribution experiments using global climate model (GCM) simulations have demonstrated that the predominance of observed global warming since about 1970 is due to anthropogenic (human caused) increases in greenhouse gas concentrations (Figure 12, IPCC 2007). These modeling experiments combined with evidence from observed greenhouse gas concentrations and global temperatures are the primary justification for strong consensus statements in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4):

> "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level." (IPCC 2007)
>
> "Global atmospheric concentrations of CO2, methane (CH4) and nitrous oxide (N2O) have increased markedly as a result of human activities since 1750 and now far

> exceed pre-industrial values determined from ice cores spanning many thousands of years." (IPCC 2007)
>
> "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG concentrations. It is *likely* that there has been significant anthropogenic warming over the past 50 years averaged over each continent (except Antarctica)." (IPCC 2007)

Earlier warming trends from about 1900 to the mid 1940s, however, are well explained by natural forcings (such as volcanic eruptions and variations in solar radiation). These trends demonstrate that natural forcings can also change the global climate significantly and may mask systematic changes over short time frames. Temperature trends in mid-century (from about 1945-1975) were relatively flat, suggesting that the effect of natural forcings remained dominant in this period. The IPCC report also points out that the attribution of observed temperature changes to greenhouse forcing using paired modeling studies remains problematic at regional (i.e. sub-continental) scales.

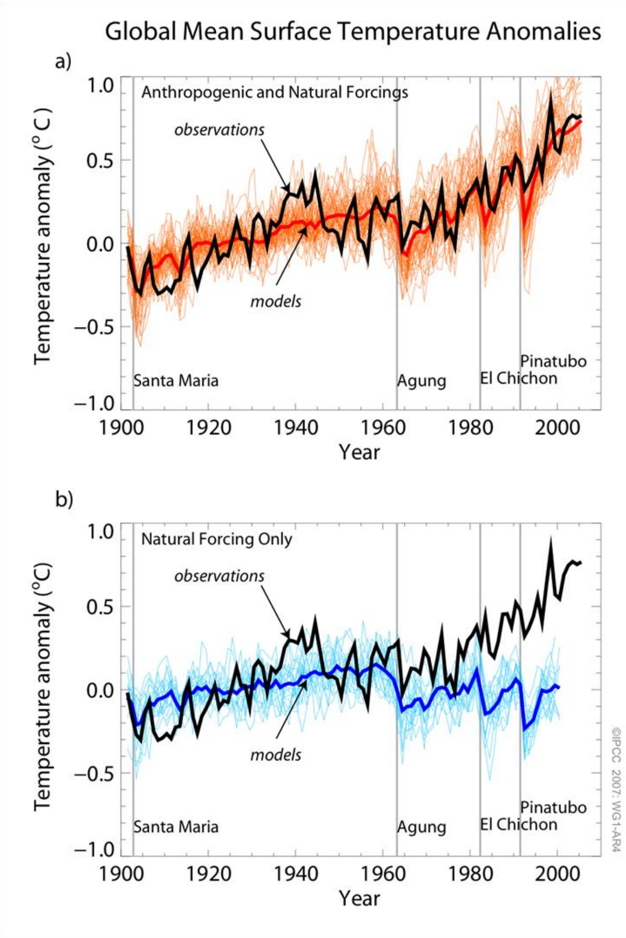


Figure 12. GCM simulations of global temperature, using both natural and anthropogenic greenhouse forcings (top panel) and using only natural forcings (lower panel). Source: IPCC (2007).

Although temperature trends at the scale of the western U.S. and the Pacific Northwest do not closely follow the global trends in any given decade, the overall trajectory of warming is very similar (i.e. a modest warming in temperature in the early 20th century (until about 1945), a plateau in the middle 20th century (1945-1975), and a rapid linear rise thereafter) (Figure 6). It is worth noting that this observed pattern seems to be most strongly related to the behavior of daily maximum temperatures, rather than daily minimum temperatures (Figure 7). Minimum temperatures show strong increasing trends over the entire historical period (Figure 7).

Significant hydrologic changes have occurred in the western U.S. over the 20th century in response to observed warming and precipitation change. Mote et al. (2005) and Hamlet et al. (2005) showed strong decreasing trends in April 1 snowpack since 1950 due to the combination of increasing temperatures and decreasing precipitation trends. Roughly half of the downward trends in snowpack were attributed to warming alone, as were the strong elevation gradients in the trends in both observations and model simulations (Mote et al. 2005). Knowles et al. (2006) showed downward trends in snowfall from station observations over the western U.S. Hamlet and Lettenmaier (2007) revealed that observed 20th century warming increased flood risks in many moderate elevation areas, but reduced flood risks in the coldest areas. Stewart et al. (2005) showed that streamflow timing shifts have occurred across the west in response to regional warming, increased frequency of rain in cool season, and causing earlier snowmelt. Barnett et al. (2008), using detection and attribution techniques and paired GCM studies (similar to those shown in Figure 11), demonstrated that on the order of 30-60% of the observed trends in Temperature, SWE/Precipitation ratio, and Streamflow Timing were directly attributable to anthropogenic greenhouse forcing. By comparison, precipitation trends (which have varied across the west at different times in the 20th century (Figure 6)), generally are not statistically attributable to greenhouse forcing using paired modeling studies. These findings support the hypothesis that observed variations in precipitation in the western U.S. are most strongly controlled by natural variability and are not human caused.

Climate Change Scenarios for the Pacific Northwest

[The discussion in this section is excerpted from Section 1.1 of Hamlet (2010) with the addition of Figure 14]

Climate change projections for the PNW, from global climate model (GCM) scenarios from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) are shown in Figure 12 for two emissions scenarios: A1B (a medium-high emissions scenario), and B1 (a low emissions scenario) (Mote and Salathé 2010).

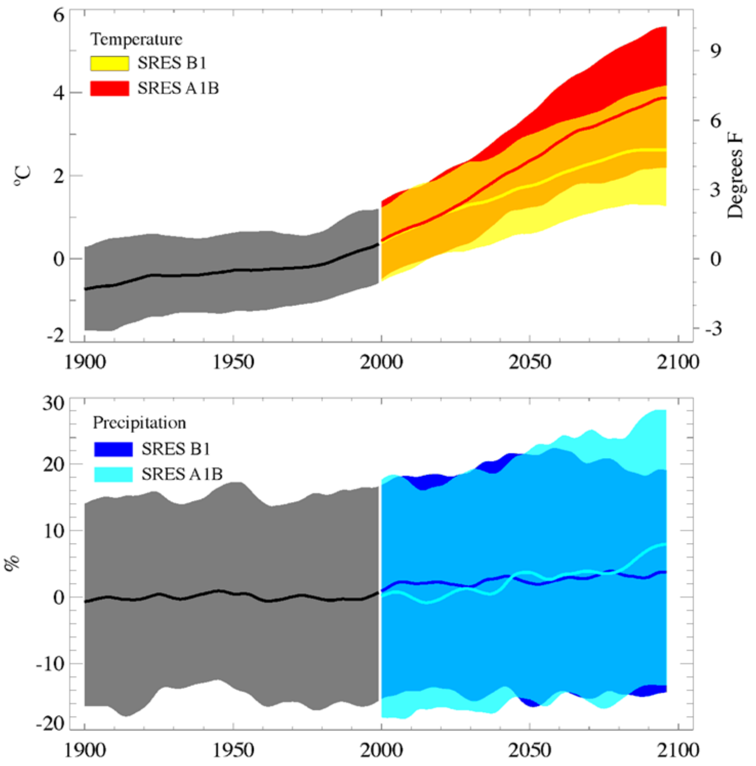


Figure 12. Summary of 20th and 21st century annual temperature and precipitation simulations from 20 GCMs over the PNW for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations, the colored bands show the same range of future projections for each emissions scenario. (Source: Mote and Salathé 2010).

The effects to regional temperature show a very high signal to noise ratio, meaning that the systematic changes in temperature are very large in comparison with the observed range of variability. For example, by the 2040s the new 5th percentile value is close to the 95th percentile shown for the second half of the 20th century. These projections show that we are very likely to enter “uncharted territory” for high temperatures in the future, and that cooler temperatures that were commonly encountered in the historic record are likely to become increasingly infrequent events.

The effect of different emissions scenarios on the temperature results show strong differences at the end of the 21st century (nearly twice as much warming for A1B as for B1), whereas up to mid-century the results for the two different emissions scenarios are remarkably similar. These findings show that reductions in greenhouse gas emissions will likely play a very important role in reducing impacts in the long term, while in the shorter-term (several decades) little reduction in warming impacts can be expected, and adaptation to impacts that are “already in the pipeline” may be the only viable approach to reducing undesirable outcomes associated with climate change.

For annual precipitation, a very different picture emerges. The GCM simulations show a very low signal to noise ratio, meaning that the systematic changes are small relative to the range of observed variability. For the PNW as a whole, there are relatively small changes in annual precipitation, and the range of normal variations that occur from decade to decade (e.g. those associated historically with the Pacific Decadal Oscillation) will probably play a very important role in determining the actual outcomes related to precipitation in any future decade. The effects of different emissions scenarios on precipitation are likewise very modest (compare A1B to B1 at the end of the 21st century, for example).

Although systematic changes in annual precipitation are small, many GCMs show systematic increases in winter precipitation and decreases in summer precipitation (Figure 13), which have some important implications for a number of impact pathways in the PNW (e.g. winter flooding, summer low flows, fire)

It should be noted that changes in precipitation simulated by GCMs are generally much more uncertain than changes in temperature, and greater caution must be exercised in interpreting precipitation results. Another way to say this is that we should expect more potential “surprises” in the effects of global climate change on PNW precipitation than we should for temperature.

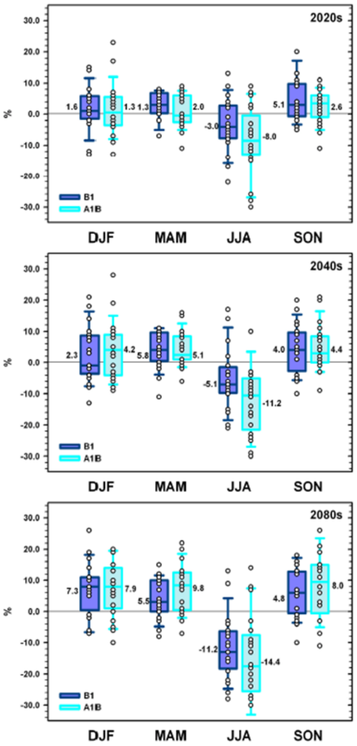


Figure 13. Changes in seasonal precipitation averaged over the PNW, expressed as percent of the long-term average historical precipitation in each season. Source: Mote and Salathé (2010).

Potential for Changing Precipitation Intensity

Monthly time step simulations of precipitation change from GCMs (as discussed above) are not well suited to an assessment of changing precipitation intensity at daily or hourly time scales. Salathé et al. (2010), however, used simulations from two regional scale climate model implementations with different forcing scenarios (GCM inputs) to assess potential changes in precipitation intensity over Washington. The results from the model simulations showed increasing precipitation intensity on the windward (west facing) slopes of the Cascades and Rockies, and decreasing intensity on the leeward (east facing) slopes in both scenarios (Figure 14). These simulations suggest that precipitation intensity will generally increase in many of the most populous areas in the PNW west of the Cascades.

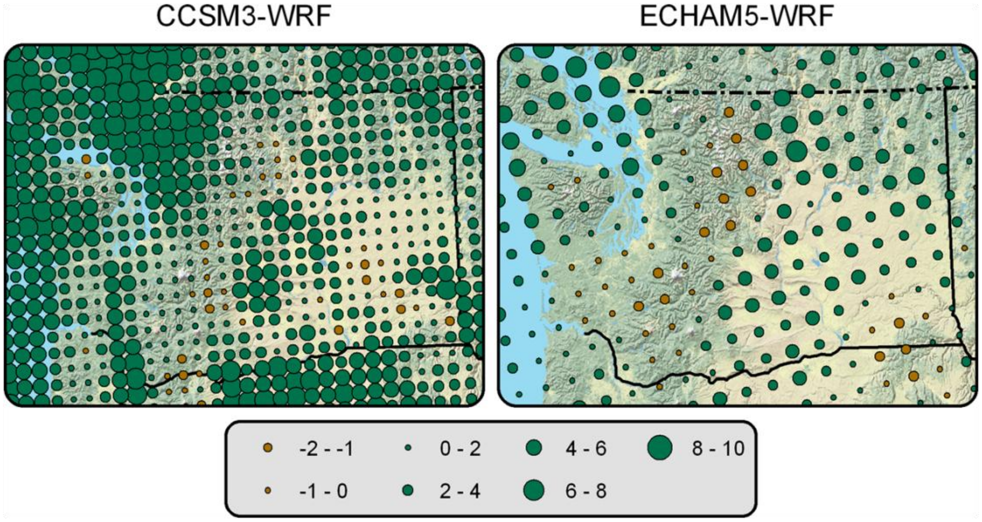


Figure 14. Change from 1970-2000 to 2030-2060 in the percentage of total precipitation occurring when daily precipitation exceeds the 20th century 95th percentile. Source: Salathe et al. (2010).

Rosenburg et al. (2010) showed using observed hourly data from stations in WA that hourly and daily precipitation extremes had increased in the last several decades, despite overall *decreases* in cool season precipitation. These changes in extremes for the relatively few available station observations, however, were not found to be statistically significant.

Changes in Mountain Snowpack and Snowfall

Elsner and Hamlet (2010) simulated mountain snowpack over the PNW for the climate change scenarios shown above. The combined effect of changing temperature and precipitation is shown in Figure 15. Reductions in snowpack are greatest in moderate elevation areas near the coast, with temperatures close to freezing in mid winter (e.g. near Snoqualmie and Stevens Pass). Colder areas (e.g. in the northern tip of the Columbia basin in British Columbia) are less sensitive, and peak snowpack can even increase due to precipitation increases in these areas.

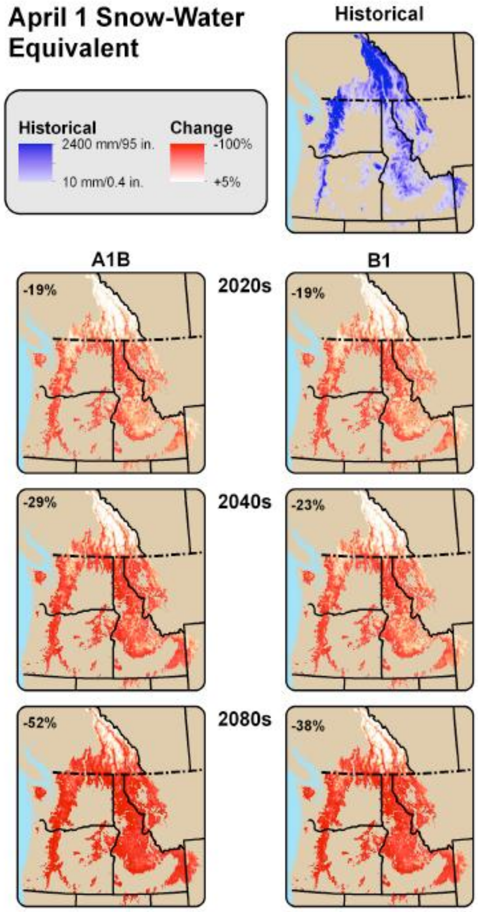


Figure 15. Simulations of April 1 Snow Water Equivalent (SWE) for historical 20th century climate (1916-2006) and changes in SWE for six climate scenarios based on two emissions scenarios and three future time periods. Changes in SWE (%) averaged over the PNW are given by the inset numbers in the upper left corner of each figure. Dark red areas show large reductions in snowpack. Source: Elsner and Hamlet (2010).

These changes in snowpack also imply widespread transformation through time from snow and mixed rain and snow watersheds (blue and red areas in Figure 16) to primarily rain dominant watersheds by the end of the 21st century. These changes are particularly pronounced in OR, for example, which experiences a transformation from about 75% mixed rain and snow for the 20th century climate, to almost 100% rain dominant behavior by the end of the 21st century (Figure 16).

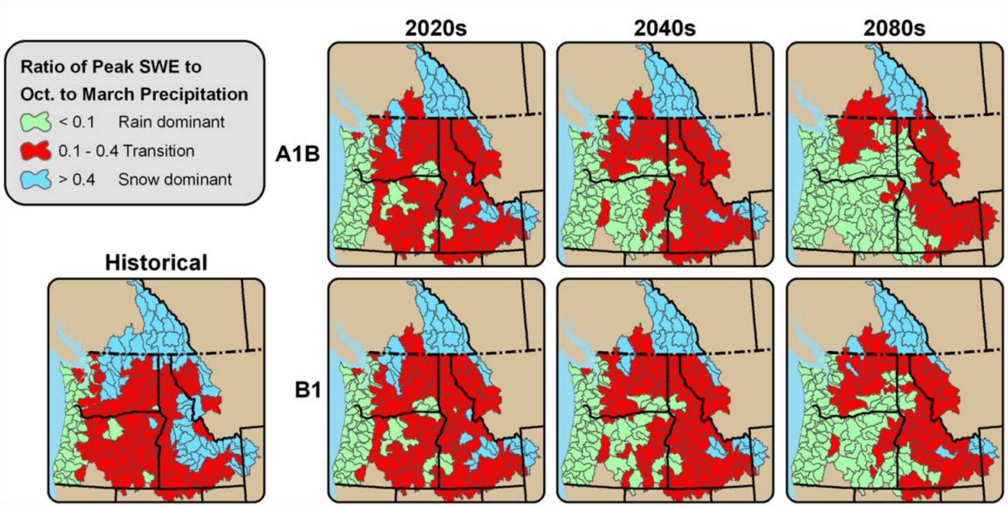


Figure 16. Characterization of changing hydrologic behavior based on the simulated ratio of the peak Snow Water Equivalent (SWE) to Oct-March Precipitation over the PNW for historical 20th century climate (1916-2006) and six climate scenarios based on two emissions scenarios and three future time periods. Rain dominant areas are characterized by ratios of less than 10 percent (green areas), mixed rain and snow (transient snow) between 10 and 40 percent (red areas), and snow dominant greater than 40 percent (blue areas). Source: Figure reorganized by Rob Norheim from a similar figure in Tohver and Hamlet (2010).

The changes in temperature in the scenarios discussed above also imply major changes in snowfall in the western U.S. Bales et al. (2006), for example, mapped areas in the west, showing the fraction of the precipitation that occurred when temperatures were between -3° C and O°C (Figure 17). By the end of the 21st century, much of the western U.S. is expected to be about 3° C warmer than historical conditions, supporting the argument that there will be major reductions in snowfall in these sensitive (and widespread) areas in the West .

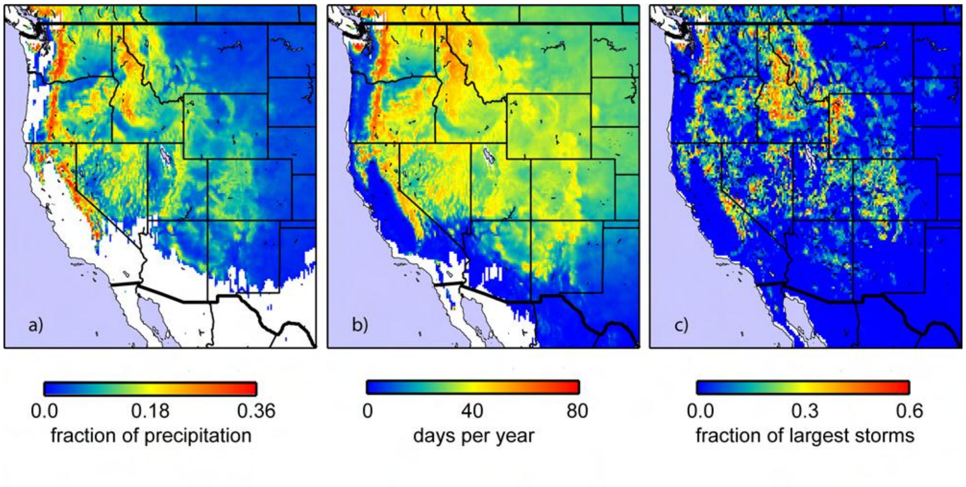


Figure 17. Maps showing the fraction of observed precipitation, number of days per year, and fraction of largest storms occurring between -3° and 0° C across the Western U.S. Source: Bales et al. (2006).

Changes in Hydrologic Extremes

Increases in hydrologic extremes are a complex function of the seasonality of changing precipitation in the scenarios (increasing precipitation in winter) and changes in snowpack and form of precipitation (rain or snow) related to warming. Thus non-stationarity of climate also generally implies non-stationarity of hydrologic extremes (Jain and Lall 2001). Figure 18, for example, shows changes in flood risk over the PNW based on daily time step hydrologic model simulations for 297 river locations in the PNW, and six future climate scenarios (Tohver and Hamlet, 2010). Low lying, rain dominant basins show modest increases in flood risk associated with increased winter precipitation, but are not significantly affected by temperature (Mantua et al. 2010; Hamlet and Lettenmaier, 2007; Tohver and Hamlet 2010). The increasing effective basin area that accompanies rising freezing levels in moderate elevation areas in mountain watersheds, combined with greater cool season precipitation, tends to strongly increase flood risks, whereas colder basins in the interior often show modest change (mostly increases in flooding, but in some cases even decreasing) flood risk in spring due to systematic loss of snowpack (Hamlet and Lettemaier 2007; Tohver and Hamlet 2010). For many large rivers impacting the major population centers in the PNW west of the Cascades, the magnitude of the 100-year flood under natural conditions increases in the simulations by 20 to 30 percent by the 2040s. (It should be noted that the potential increases in precipitation *intensity* shown in Figure 15 are not included in these projections (i.e. the projections are very conservative in this regard).

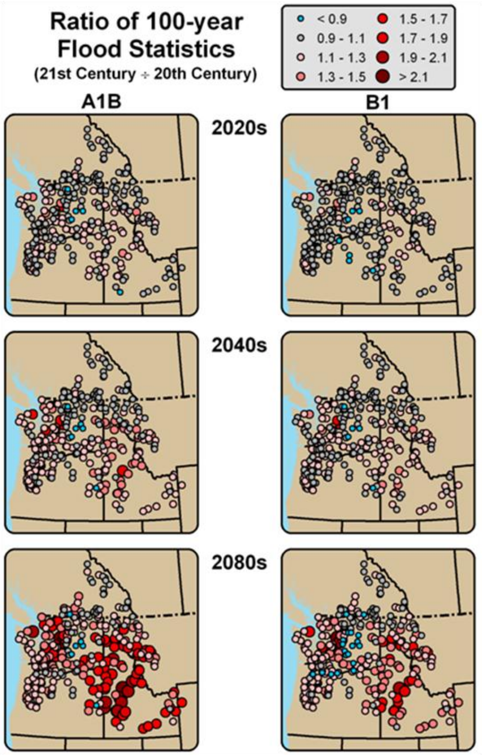


Figure 18. Maps of the ratio of the 100-year flood magnitude (future/ historical) for three future time intervals under two emissions scenarios for 297 river locations in the PNW. (Higher ratios indicate more intense flooding events projected for the future). Source: Tohver and Hamlet (2010).

Changes in the Risk of Forest Fires

Littell et al. (2010) estimated changing risks associated with forest fires in Washington State by first establishing relationships between observed area burned and climate variables such as temperature, precipitation, and evaporation in Washington State. The regression equations constructed from these relationships explained about 50% of the observed variance in area burned (i.e. $R^2 = 0.5$). Using scenarios of the explanatory variables, the study estimated changes in area burned for two climate model scenarios and three future time periods, which show increases in the area burned (Figure 19). The study also showed increasing risk of forest disturbance related to mountain pine beetle attacks associated with warmer temperatures and increases in drought stress.

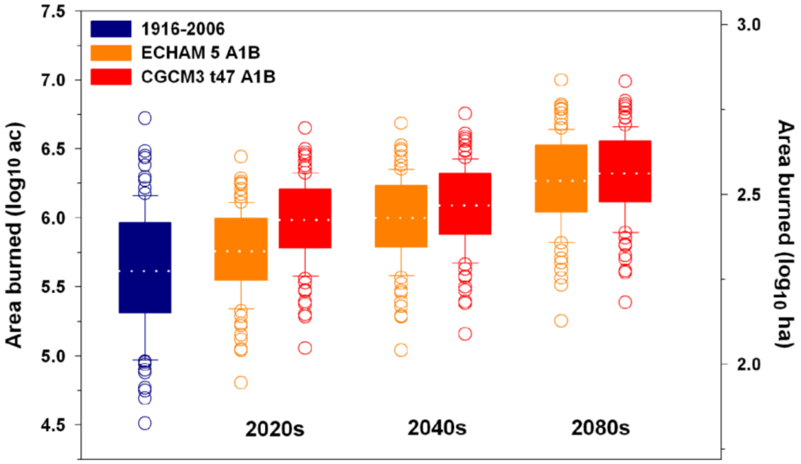


Figure 19. Regression-based estimates of area burned in Washington State for historical conditions (1916-2006) compared with two climate change scenarios (orange) and three future time periods (red). Source: Littell et al. (2010).

Fire has the ability to affect transportation in several ways. Smoke during fires can affect traffic operations and safety by obscuring visibility for drivers. Large fires can sometimes create enough smoke or emergency response to require closure of roadways, interfering with mobility and creating economic impacts (Pierce County 2006). Fires and insect damage can also have a secondary impact of reducing vegetation coverage, leading to increased erosion and landslides that can erode or cover roadways during or following heavy rains and snowmelt (Mehaffey 2010).

Changes in fluvial geomorphology, sediment transport, landslides, mudflows

Very little quantitative information is currently available about the potential impacts of climate change on fluvial geomorphology, sediment transport, or landslide/mudflow risks. A few case studies, however, have generated some useful hypotheses concerning potential impacts. To begin with, flood risks in the PNW have generally increased in the PNW in recent decades as discussed above. For many rivers west of the Cascades, the four or five largest floods in the historical record have occurred in the last several decades (e.g. in the case of the Skykomish River, Figure 1). These floods have resulted in major damage to transportation infrastructure in some areas due to rivers changing course in the floodplain. Figure 20 shows impacts to road infrastructure in Mt. Rainier National Park in 2006 (NPS 2006). Similar impacts were encountered in the same year in Olympic National Park, which resulted in restricted access to the Hoh Rain Forest, a major tourist destination for the park.

Increases in sediment transport in Mt. Rainier National Park have been partly related to increasing flood risk and partly related to recession of glaciers which has resulted in newly exposed sediments in steep mountain terrain. The changes in sediment transport have had dramatic effects. The bed of the Nisqually River below the headwater glaciers is estimated to have risen about 38 feet since 1910, and the resulting channel instability and high water levels during flood events now threaten both park access and the historic buildings at Longmire (http://www.abbegeomorphology.com/?p=69).

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Figure 20. Flood damage at Mount Rainier National Park in November 2006: the Nisqually River at Sunshine Point (left) and the broken edge of the Nisqually Road (right). Source: NPS (2006).

Some additional hypothesized impacts of climate change on geomorphology include:

- Increasing precipitation intensity is expected to increase the severity of extreme sediment transport events (e.g. landslides, debris flows, mud flows, sediment inundation of public recreation areas, etc.)
- Systematic loss of snowpack may reduce the "armoring" effect of deep snow on the landscape in moderate elevation areas, leading to increased soil saturation, landslide risk, and increased sediment loadings in creeks and rivers in winter.
- Changes in forest disturbance patterns, particularly fire, are likely to be important driver of impacts, especially in the first few years after disturbance.

Sea Level Rise

Rising sea level due to thermal expansion of the oceans is one of the most fundamentally certain outcomes of global climate change (IPCC 2007). Using results from the 2007 IPCC report, Mote et al. (2008) estimated relative sea level rise for Washington State associated with a number of driving factors, including global average sea level, effects to sea level due to atmospheric circulation, effects of vertical land movement, etc. Sea level rise was projected to likely exceed 33 cm (13 inches) by 2100, with an extreme high (low likelihood) scenario of 127 cm (50 inches).

Although preliminary projections of sea level rise from the IPCC 2007 report and the local estimates discussed above have helped to initiate much needed discussion of potential impacts, these estimates of sea level rise are already out of date only a few years after they were published. The reason is that the IPCC report relies on published studies at the time of the report, and research in this area has been progressing very rapidly. Projections of future sea level (even at the global scale) have been changing in the literature as current research has improved the understanding of the rate of loss of terrestrial ice (e.g. the Greenland Ice Cap) and ice shelves, which effect the rate of sea level rise. Figure 21 (Nicholls and Cazenave 2010) compares estimates of sea level rise from the 2007 IPCC Fourth Assessment Report to more recent projections from published studies. Note that the low end of the range for the three more recent studies is roughly equivalent to the high range of the 2007 IPCC estimates, and that the range of uncertainty is also greater than the 2007 IPCC projections. Regional sea level rise (say at the scale of the west coast of North America) is even more uncertain, particularly in the context of relatively short time scales of a few decades where drivers related to decadal variability may play an important role in determining local impacts. Observed short-term trends in absolute sea level have actually been *downward* on the west coast of the U.S. from 1992-2009, for example, apparently in response to short-term variations in atmospheric circulation patterns (Nicholls and Cazenave 2010). In other areas of the globe, observed trends in sea level exceed the global mean rate (about 2 mm/year) by as much as a factor of five.

While projections of sea level rise will probably continue to evolve in response to ongoing monitoring and improved scientific understanding of key drivers, there is little question that this issue will be a major factor in adapting to impacts in the near coastal environment. The large uncertainties in sea level rise projections suggest that flexible management strategies and infrastructure designs are needed that can be adjusted in response to new information over time (see discussion below).

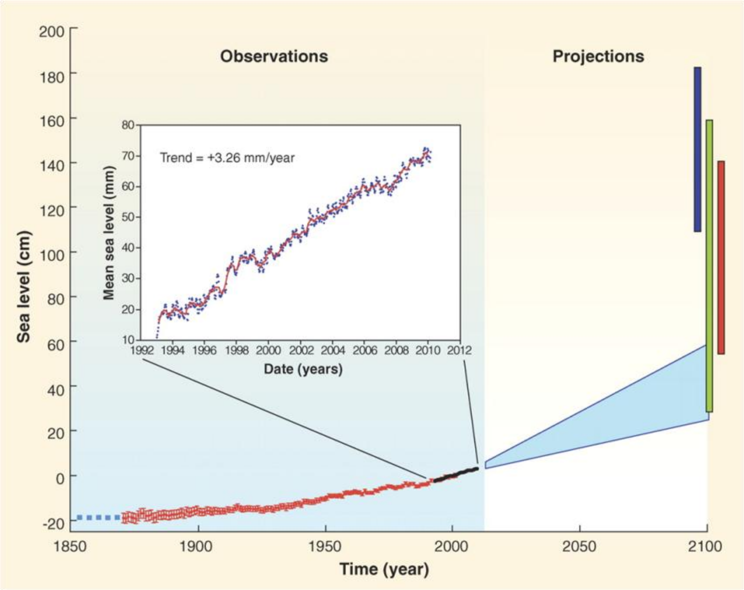

Figure 21. Estimates of historical and projected future global average sea level . Blue band shows the range of uncertainty for the very conservative projections from the IPCC Fourth Assessment Report. Blue, green, and red bands show the range of uncertainty at the end of the 21st century from three recent studies incorporating improved estimates of the rate of loss of terrestrial ice mass. Source: Nicholls and Cazenave (2010).

4. TRANSPORTATION IMPACT PATHWAYS

4.1 STRUCTURES

A number of kinds of structures and design processes associated with them are likely to be affected by climate variability and climate change, a few of which we discuss here.

Bridges

Bridges are primarily affected by changes in meteorological and hydrological extremes including: precipitation intensity, changes in river flow, and changes in sediment and debris loadings. In coastal areas, sea level rise will also affect water height and saltwater intrusion, affecting corrosiveness of water on concrete and steel structures. Changing precipitation intensity may affect the drainage performance of the bridge deck or approaches in such a way that traffic safety is impacted, and different design standards or related factors of safety may be needed to account for such changes during the design process. Increases in river flooding, which may be related to both changes in temperature and/or precipitation (see discussion above), may increase the frequency or duration of extreme events that overtop the existing bridge deck. Bridge pylons, approaches or other structural elements may be damaged by increased scour or by the accumulation of large debris (such as uprooted trees) during extreme events. Increased scour could occur either because of increased flow rate or increasing sediment transport rates in winter related to loss of snowpack, increasing landslides in steep headwater areas, etc. Increased sediment loading could also potentially protect structures by depositing material around pylons, etc. Although detailed case studies quantifying these impacts are generally lacking, an increase in the amount of woody debris transported during floods is hypothesized to relate to flow rate, increased inundation of forested land, increased tree mortality, changing soil saturation conditions that may accompany loss of snow cover, altered soil moisture dynamics, and/or increased precipitation intensity. Design standards for both flow and debris content may need to be revised and/or factors of safety in the design process increased to account for such changes.

Roadbed and Pavement

The design of the roadbed and pavement may be impacted by changing climate. Temperature extremes (presumably higher temperature extremes) may dictate a revised choice of pavement materials in some cases. Changes in the occurrence of frozen ground or water table height during the wet season may affect the stability of roadbed materials. Potential increases in precipitation intensity may affect storm water management considerations related to drainage. The need to account for snow removal in the design of pavement or shoulders may change over time.

Although changing conditions may be encountered during the lifespan of a particular project, designs with relatively short life cycles may be able to use monitoring of recent conditions (e.g. using probability distributions based on data collected over several recent decades) or the monitored performance of existing infrastructure to select appropriate materials and design parameters (see discussion below).

Construction and Maintenance Schedules

Construction and maintenance schedules are likely to shift in seasonality in some cases due to warming temperatures. For areas with relatively warm summer temperatures (e.g. east of the Cascades), construction and maintenance projects that require extensive pouring of concrete may require additives or shifts in technique to accommodate the warmer temperatures. Conversely, warmer winter temperatures, less frequent frozen ground, and decreased snowpack may increase construction opportunities in fall, winter, and spring, particularly in drier areas where cool season precipitation is less of an obstacle to construction. Scheduling construction projects in the winter months may, however, require additional slope stabilization or sediment mitigation efforts (because of projected increases in winter precipitation and storm intensity).

4.2 STORMWATER MANAGEMENT

As noted above, relatively little is currently known about the changing nature of precipitation extremes in the PNW, and efforts to provide explicit scenarios of changing daily or hourly precipitation statistics are only now underway. While there is some evidence that storm intensity and flood risk have increased historically since about 1975 (following changes in the variance of cool season precipitation for the PNW as a whole), there is little to suggest that such changes are directly related either to greenhouse forcing or warmer regional temperatures. Thus, in low-lying, near-coastal environments where most urban and suburban development has been focused, it remains unclear whether observed changes in 20th century precipitation statistics should be considered systematic in nature (suggesting potential design changes for stormwater systems to account for increased precipitation variability or intensity and related flood risks), or whether such changes are related primarily to decadal variability or other factors that result in cyclical behavior (suggesting that design standards should probably continue to be based on long historical records). These uncertainties support the argument that until more conclusive information about future impacts is available, attempts to identify more robust solutions to existing stormwater problems may be the best approach for adapting to potential changes in storm intensity in the future. So for example, improving the capacity of existing roadside stormwater systems by using bioswales or other alternate technologies that reduce runoff production would provide benefits now, while increasing adaptive capacity to hypothesized increases in storm intensity for the future (based on projected monthly increases in precipitation) (Whitley Binder et al. 2010).

4.3 SNOW REMOVAL, AVALANCHE, AND MUDSLIDES

Snow removal and other operational services related to snowfall is one of the few areas where systematic reductions in cost may be encountered over time. Low lying areas that commonly experience winter storms a few degrees below freezing will likely see reduced snowfall, presumably resulting in lower operational costs for snow removal on average. In mountain passes, snow closures may decrease in frequency. The nature of extreme snowfall events, however, may potentially change (possibly even increasing in severity), requiring the maintenance of emergency response capacity. Exceptionally heavy spring snowpack in 2011, for example, resulted in a debris-laden avalanche which closed Hwy 20 in May (Figure 22). The need for operational services associated with snowfall may be replaced by increasing demand for services related to other hazards. For example, areas with frequent mid-winter snowstorms under current conditions are likely to experience decreases in snowfall (requiring less snow removal capacity), but could experience increases in the frequency of ice storms (requiring more capacity to remove downed trees or powerlines), and more emergency management response capacity to deal with increased impacts to public safety from flooding and landslides.

Figure 22. Avalanche on Highway 20 in northern Washington during May 2011 (photo by Sam Martinsen).

Potential impacts related to changing risks of avalanche and mudslides impacting highways are currently essentially unknown. One hypothesis is that shifts from avalanche risk to landslide risks may occur over time in steep mountain environments (e.g. Snoqualmie Pass and Stevens Pass) due to systematic loss of snowpack and increasing exposure of soils to precipitation falling as rain. Winter mudslides are a common occurrence in the relatively warm Northern Sierra in CA, for example, but are rare in the relatively cold North Cascades, WA. Current infrastructure that is capable of dealing with avalanche risks (e.g. snow sheds) would not necessarily be effective in coping with landslides or mudslides, because of the need for material removal that is required in the case of landslides or mudslides.

4.4 RIVER FLOODING, COASTAL FLOODING, AND EROSION

Initial projections of river flooding across the PNW using GCMs temperature and precipitation scenarios and hydrologic models show increasing flood risks in most locations due to the combined effects of warmer temperatures and increasing monthly precipitation in winter. Increased flood risks are particularly pronounced on the western slopes of the Cascades where rising snow lines and increases in winter precipitation combine to dramatically increase peak river flows (Tohver and Hamlet 2010). In other areas (e.g. some areas of eastern WA) changes in flood risk are likely to be relatively small. Sea level rise combined with vertical land motion is projected to increase water levels and coastal erosion in many areas, but some areas experiencing relatively rapid uplift may experience little sea level rise relative to the changing land surface elevation. Increased flooding is expected to impact transportation infrastructure in low-lying areas near existing river channels, or in near-coastal areas. Recent inundation of I-5 in 2007 and 2009 due to flooding near the Chehalis River (although not necessarily caused by climate change per se) has provided some direct experience of impacts that are projected to become more frequent across the region in the future. In near-coastal areas, sea level rise may threaten transportation infrastructure due to increased frequency of inundation and/or increased erosion. Some examples of infrastructure that are likely to be vulnerable both to sea level rise and river flooding include low-lying secondary roads (near rivers or the coast), roads built on dikes near the mouths of rivers, and rail lines built on berms abutting Puget Sound north of Seattle.

4.5 FOREST AND PARK ROADS

Forest roads are likely to be impacted by increased flooding, increases in woody debris, and/or altered sediment transport regimes. Increased flooding may exceed current design specifications for infrastructure like culverts, causing increasing failure rates and higher replacement costs (if design standards do not incorporate increasing risks). Glacier recession, loss of snowpack, increasing land area with saturated soils, and increased flooding may also increase sources and transport of woody debris and sediment, resulting in more frequent plugging of culverts and increased impacts to built infrastructure and aquatic ecosystems. In Mount Rainier National Park, for example, changing river sediment dynamics associated with glacial recession and increased flooding currently threaten both park buildings at Longmire and road access to substantial portions of the Park. Small-scale estimates of changing flood risk are needed to help address design decisions. A collaborative project with engineers and managers in the Olympic National Forest is currently underway to address this need. Updates to maps of high risk areas for slope stability failure may also need to be updated to reflect loss of snowpack and/or more active soil saturation dynamics in winter as precipitation shifts from snow to rain.

4.6 EMERGENCY MANAGEMENT AND WARNING SYSTEMS

Many aspects of current emergency management and warning systems will be relatively adaptable to changing conditions, and some will even adapt to changing climate conditions largely autonomously without significant change. Other aspects of emergency management systems, however, may need substantial revision or new procedures to cope successfully with non-stationary risks or emerging hazards.

Self-Tending Forecasting Systems

A non-stationary and rapidly evolving climate system calls for physically based forecasting tools for natural hazards that do not require repeated intervention to function well. For example, predictive tools for natural hazards which are based on regression equations (statistical models trained on historical data) are generally inferior to more physically based tools such as numerical weather prediction models. Fortunately, many of the tools that are needed to address natural hazards that affect the transportation system are of the latter type. State-of-the-art systems for short-term flood forecasting, for example, use numerical weather prediction models coupled to physically based hydrology models. Such tools are “self-tending” in the context of changing natural variability or climate change because numerical weather prediction models are expected to account automatically for the changing nature of the climate system (i.e. improved weather prediction models that can successfully simulate the altered temperature and precipitation statistics associated with climate change already constitute a well-recognized, and well-funded, scientific need). As these tools are improved over time, emergency management systems that depend on short-term weather forecasts also improve automatically. Thus, emergency management procedures related to weather forecasts such as traveler advisories related to snow, ice, severe weather, or flooding will arguably function as well as (or perhaps even better than) they do now.

Other types of hazards, however, may require improved or different kinds of monitoring and warning systems. An example might be hazards related to potentially increased precipitation intensity and/or stormwater drainage problems that result in increased risks associated with standing water on the roadway. Successfully monitoring such rapidly evolving events in real time and then alerting drivers in a timely manner of the hazard would require substantial investment in new technology and warning systems, and such systems would not necessarily be self tending. These improvements in real time monitoring are already a priority, but changing conditions may necessitate more widespread use and more rapid implementation schedules to cope with increasing impacts.

Emergence of New Hazards and Changes in the Intensity of Extreme Events

Emerging hazards or dramatically increased intensity of extreme events, such as those related to the combination of sea level rise and/or land subsidence, changes from snow to rain, ice storms, winter flooding, warm-season flash floods, dam failures, or changes in avalanche, debris flow, or landslide risk may present new challenges to emergency management systems. Concerns relating to preparedness to deal with emerging hazards are a) that needed emergency management systems and/or infrastructure are not in place to cope with these new hazards, or b) that existing emergency management systems that are already in place to protect the public fail to work as intended in the new situation. An example of this kind of impact relates to evacuation routes in low lying areas in case of tsunami or flooding. Extreme events are by their nature are very infrequent, and there is the potential (without monitoring and evaluation using scenarios) for sea level rise or changing flood risk over a number of decades to make these evacuation routes less effective under emergency conditions. Also, currently safe areas may no longer provide the same level of protection that they have in the past (e.g. how far inland should people be evacuated to protect against a large subduction zone earthquake and resulting tsunami?). Similarly, infrastructure and procedures designed to protect against avalanche may be ineffective in dealing with emerging risks associated with emerging risks from mud flows or landslides. Thus, emergency planners may need to consider and plan for new hazards and/or conditions that are outside of their current management experience. Official products providing information on extreme conditions generally do not include climate change information, and thus, cannot be relied on to anticipate potential changes in these vulnerable areas.

5. DESIGN CONSIDERATIONS

Design professionals in the PNW (and U.S. as a whole) will face many profound challenges associated with planning for relatively rapid changes in risks during an evolving climate system. Historically, climate related design standards (e.g. related to precipitation, temperature, and flow extremes) used to inform various design decisions have evolved gradually over time, and are based in part on long historical experience with relatively stationary climate conditions in the 20th Century. Design standards also represent defacto social contracts with society that reflect specific cultural and socioeconomic attitudes about risk. For example, the 100-year flood is often used in land use planning in the U.S., despite the fact that in other parts of the world different levels of risk tolerance inform similar policies. These social contracts, too, have been established over time based on our collective experience of a relatively stationary climate system.

Currently, most design standards and the design processes they support are focused on the analysis of historical conditions and experience gained using this information in specific kinds of design decisions. Most of the tools that are available for predicting hydrologic extremes, for example, are based on historical records and are not necessarily suitable for predicting future conditions. Perhaps the greatest challenge that design engineers will face in the coming decades will relate to the need to adopt new approaches, methods, and analytical tools that look forward in time to incorporate projections of substantially different conditions from those encountered historically while simultaneously looking backward in time to historical conditions (Jake et al. *in review*). In this section we explore several broad adaptive strategies for integrating a rapidly changing climate in the design process. With limited resources, such strategies could be applied first to infrastructure types that are considered most vulnerable to changing climate.

It is important to note that the alternative strategies put forward below do not constitute recommendations for revised procedures, which would be premature. Rather, the intent is to promote discussion about potential concerns or vulnerabilities related to climate, share ideas regarding alternative approaches to address these concerns, and facilitate ongoing learning and evaluation of potential adaptation strategies.

Strategy 1: Update Existing Decision Support Tools Using Recent Retrospective Data

This strategy would extend current practice under which certain decision support tools are regularly updated to incorporate potentially changing conditions. A common approach is to update at regular intervals (e.g. once a decade) using retrospective climate data for the past 30 years. This approach is used, for example, in estimating climate “normals” (averages) reported by NOAA. The approach can also be applied to regression equations or other predictive tools, whose parameters can be updated based on the most recent 30 years of observed training data.

Although commonly used in practice, and well known to practitioners, this approach has some important limitations in the context of climate change adaptation. To begin with, the approach works best for variables such as temperature that are expected to increase gradually and largely monotonically over time. Even in this best case scenario, the approach is inherently backwards looking, which implies that it will tend to systematically underestimate future temperatures in a steadily warming climate. Similarly, the larger the rates of change, the more severe the predictive error. Future trends in temperature are estimated to be on the order of 1˚ F per decade in the 21st century, so forecasts of future conditions 20 years in the future based on the last 30 years of data could be off by more than 2˚ F.

Retrospectively updating products that are coupled to climate variables that are known to vary in a cyclical manner (such as precipitation) tends to introduce systematic (and cyclical) errors in future predictions. In these cases retrospective updating is not well advised because conditions for the previous 30-years is likely to be a poor predictor for the next 30 years. This weakness is particularly evident in accounting for natural variations in cool season or annual precipitation associated with the PDO (described above), using a 30-year backward looking window, because the PDO has a characteristic half period of 25-30 years.

In some cases *trends* in temperature data have also been used in an attempt to improve forecasts. The NOAA Climate Prediction Center's "Optimal Climate Normals" product, for example, incorporates 10-year trends in temperature, which have been shown to increase skill at seasonal to inter-annual time scales. Such approaches could potentially be used over longer time horizons by combining projected trends with observed baselines. Observed trends in precipitation tend not to persist (Figure 7), and therefore trend extension approaches should probably be avoided in the case of precipitation.

Strategy 2: Create Forward Looking Design Standards Using Models

In this strategy, model simulations of important design variables are used to replace historical records. For example, historical estimates of Q_{100} (the 100-year flood) or Probable Maximum Precipitation (PMP) are replaced with estimated values from climate and hydrologic model simulations incorporating the effects of increasing greenhouse forcing on temperature and precipitation. These approaches are essentially mapping exercises that relate the current social contracts informing engineering decisions in the historical context (e.g. the decision to use Q_{100} as the basis for land use decisions) to analogous information projected for the future conditions (i.e. the value with the same return frequency is extracted from future projections of the probability distribution). This approach may be most appropriate in design decisions with very long lifecycles, particularly in the case where profound changes in relevant design standards are expected (Jake et al. *in review*). For example, failure to account for sea level rise in building expensive, long-lifecycle infrastructure in low lying coastal areas is a recipe for potentially disastrous outcomes. Likewise, locating extensive future development and related transportation infrastructure in areas with projected dramatic increases in flood risk (as in mid-elevations in western WA) is likely to increase vulnerability to these projected changes in hydrologic extremes.

Projecting design standards forward in time may also imply that design parameters that are not important now may become so later (and vice versa). In mountain passes, for example, the risk of mud slides or debris flows in rivers may increase, while avalanche risks may decrease, as discussed above. Fundamental changes in the relationships between physical variables can also erode performance of decision support systems.

In other areas where the impacts are not clearly delineated and/or quantitative forecasts are less reliable, a number of problems may emerge in attempting to implement such a strategy. To begin with model simulations must replace observations as the basis for design standards, an approach with which many design professionals are fundamentally uncomfortable. This uneasiness often relates to the fact that the error characteristics of projected changes in meteorological or hydrological extreme events are essentially unknown. While the performance of the tools used in making projections can be evaluated in a historical context, there is still a fundamental difference between historical observations of eventsthat have actually happened (albeit with some uncertainty due to limited station coverage, measurement errors, etc.) and model projections of future conditions, which are based on computer simulations of environmental conditions that have not occurred yet. Secondly, projections of changing climate risks are often based on an ensemble of realizations (e.g. 10 or more simulations of future conditions from different global climate models), whereas historical records have a sample size of one (i.e. one time series). Thus the mapping process from an historical design standard to a future one is not necessarily straight-forward even at a technical level. This retrospective approach can also lead practitioners to a mistaken sense of certainty when using historical observations as predictors for future conditions.

Finally, if design standards are to change over time in response to ongoing modeling studies, there is a bureaucratic process for reviewing and giving official sanction to such changes that will not be easily achieved in a non-stationary environment. Thus, in potentially implementing such an approach, important institutional considerations will need to be addressed regarding the establishment and updating of changing design standards in real time, and the need to address issues associated with professional risk in the design process (i.e. the development of officially sanctioned design standards for particular purposes).

Strategy 3: Bayesian Approaches: Monitoring and Adaptive Management

This strategy is analogous in some ways to the gradual evolutionary process that has created the current design standards and design criteria for transportation systems, and is based on Bayesian approaches that update current practices in response to new information. In this approach, the observed performance of infrastructure (or other systems) implemented using current design criteria are carefully monitored and evaluated on an ongoing basis. If changes in performance are apparent, design criteria (e.g. choice of materials or “factors of safety” used in the design process) are revised to account for these observed changes in performance. Because such approaches are inherently “backwards looking,” they tend to work best in situations where the lifespan of the design decision is relatively short (e.g. a decade or two) and is associated with relatively low risk, where monitoring is already taking place, and where climate variations that affect outcomes are easy to detect and are not inherently cyclical in nature. For example, such an approach would probably work well in the context of choosing appropriate paving materials for secondary roads in response to gradually warming temperatures, whereas it would not work well in the context of designing freeway bridges with a relatively long design life, or in designing stormwater systems whose performance is affected by cyclical patterns of precipitation that change from decade to decade.

Although conceptually straightforward at one level, such systems are also potentially expensive to implement because they require a carefully constructed monitoring and retrospective assessment system that in many cases does not currently exist. It is also worth noting that from a policy standpoint, the decision to revise design criteria that materially affect costs in response to changing performance has often been a contentious one in the past. The discussion below related to “replace in kind” policies for failed culverts on federal lands is one example of this difficulty.

Although not recommended by the author, “crisis management” is an example of a Bayesian system of adaptation. In this ad-hoc system, high-impact, high-visibility engineering failures force the political and regulatory system to make step changes related to design standards or engineering criteria. A recent high-visibility bridge failure in Minnesota in 2007 (I-35W over the Mississippi), for example, prompted nation-wide review of aging infrastructure inspection and maintenance needs. Similarly, Hurricane Katrina and the destruction of New Orleans focused national attention on levee design standards and maintenance programs. The obvious downside of this approach is that instead of making smaller, incremental changes in a proactive manner that would potentially avoid some of the undesirable future outcomes, meaningful action is delayed until a catastrophe occurs. In some instances crisis management can dramatically increase vulnerabilities. An example would be a floodplain management strategy based on crisis management that effectively allows more and more people and infrastructure into the floodplain over time (under the assumption that flood risk is not changing) until a high-impact event occurs. Despite many limitations, this adaptation approach is almost certain to function in the future for the same reasons that it has historically.

Strategy 4: Flexible Infrastructure Design

In response to the many challenges and uncertainties related to backwards looking updates and projecting future meteorological or hydrological extremes that affect design decisions using models, an idea recently put forward (especially in the context of addressing sea level rise) is the idea of building flexible infrastructure. In this strategy, a certain amount of design capacity is built in the short term, but in such a way that the capacity of the system can be increased later in an incremental manner. A good hypothetical example of the use of this design paradigm would be the design of an expandable sea wall to protect infrastructure against sea level rise. The initial design is implemented to protect against extremes expected over a relatively short planning horizon (perhaps 20 years), but the design intentionally incorporates the ability to raise the height of the sea wall at relatively low cost in response to monitoring of actual sea level rise or revised projections of future conditions. Such a design concept probably costs more to implement initially, but does not require an initial investment in the full extent of future design needs. Such an approach avoids the potential for overdesign of infrastructure in response to uncertain future projections, and effectively takes advantage of the future value of money in building additional capacity that may be needed. This kind of approach is perhaps most workable and effective in the context of slowly changing, and monotonically increasing impacts over long time frames, such as sea level rise.

One important caveat on this approach is that the overall design must have the capacity to encompass projected changes over a long time frame if it is to be sustainable. In some cases, specific technologies or approaches that are effective in the time frame of 20-50 years become ineffective (or less effective) over longer time scales of 100 years or more. For example, protection of existing infrastructure against sea level rise using a sea wall may be possible for a while, but may not constitute a sustainable option over longer time frames when the impacts become prohibitively large.

Strategy 5: Robust Systems Design

Another strategy for coping with the many difficulties and uncertainties related to quantifying future meteorological or hydrological extremes is to increase margins of safety across the board to account for the general direction of change. Such a decision responds in a qualitative manner to projections of increased future risk (such as increased flood risk), but without attempting to fully quantify the risks or create revised design standards. An example of such an approach is a decision to move critical or long-lived infrastructure outside the inundation area associated with the 500-year flood event, replacing policies based on the 100-year event. Such an approach is different than Strategy 2 in that it focuses on the social contract aspects of the design process rather than on the technical issues related to potentially changing design standards. If a consensus can be reached that the current level of risk is too high, for example, then a change in design criteria to reduce those risks is likely to become socially and professionally acceptable. Such a consensus can be difficult to establish, but a review of international standards related to flooding is instructive in this context. The differences between policies and design standards in the Netherlands and the U.S. are striking, and demonstrate that our level of risk tolerance is subject to reconsideration in light of changing events.

In some cases robust design decisions can derive from overlaps with other design criteria. In the case of the culvert design process in the Olympic National Forest discussed in previous sections, culverts designed primarily for better fish passage (large, half-moon-shaped culverts that provide a more natural stream channel) generally far exceed high flow design standards. Thus, installing these systems in areas where avoiding fish passage impacts is a high priority creates a system that is inherently robust to potential changes in high flows. While these culverts are more expensive, a decision to use this “best management” approach for fish in areas with strong increases in projected flood risk may make sense by avoiding the issue of uncertainty in design standards while providing other important benefits.

Strategy 6: Focus Additional Design Resources on Susceptible Areas

While increasing factors of safety or revising design standards in susceptible areas (areas where substantial climate change impacts are projected) using modeling studies is one approach, another strategy is to focus additional attention on other elements of the design process in these areas in an attempt to increase the robustness of the design. Elements such as more thorough evaluation of the design site, additional study of causes of failure in similar areas, or more complete analysis of other factors that may contribute to infrastructure failure (e.g. landslides or debris accumulation during floods) are likely to yield safer and more robust designs. This approach makes maximum use of a wider range of available information. Such efforts take more time and therefore, may increase costs, but are potentially more workable because they do not require increased risks to be quantified with a high level of certainty. Instead, scenarios of increased risk are only used to identify susceptible areas where more careful design work would likely pay dividends in terms of reducing future infrastructure failure rates.

6. POLICY DIMENSIONS

A comprehensive investigation of the potential changes in policy that may be required to facilitate climate change adaptation in the transportation sector is well beyond the scope of the initial investigation in this paper. That said, there are several overarching issues related to policy decisions that are worth mentioning in the context of climate change adaptation.

To begin with, federal policies must ultimately serve a very wide range of applications across the entire country. As we have seen in the previous discussion, however, the impacts of climate change vary strongly from place to place, even at the regional scale. Impacts on the east coast and west coast of the U.S. may be fundamentally different, for example. Coastal areas may be impacted most strongly by sea level rise or hurricanes, whereas inland areas may be impacted mainly by extreme convective storms. This suggests that federal policies addressing climate change adaptation will probably need to be flexible enough to allow decision makers and practitioners to account for unique regional impact pathways in responding to federal guidelines and regulations. For example, regulatory standards directing designs could simplify variances approvals from those standards to facilitate designs that address unique site information or new impact pathways.

Many practitioners in the engineering design professions currently view their professional responsibilities primarily in the context of responding to the many elements of the current regulatory environment, which are beginning to incorporate climate change adaptation. Although such changes will probably be an important part of the response to changing risks, it is also important to realize that changes to the regulatory framework itself may also be needed. A good example of the kind of regulations that may need to be revisited is the "replace in kind" policies that currently apply to replacement of infrastructure on federal lands (e.g. culverts in forest roads). Under these policies a culvert washed out by flooding would be replaced by the same size culvert to avoid triggering certain environmental processes or permits, or to qualify for federal funding, instead of designing the replacement culvert (or other structure) based on monitoring, estimates of changing floods, or fish passage needs. In western Washington, where flood risks are projected to increase in most areas, such policies are a barrier to revising the design process to cope with these changes. "Replace in kind" policies are presumably intended to reduce costs in the short term by streamlining the design and permitting process and effectively places a ceiling on replacement costs, but unless these rigid constraints are removed, adaptation to changing risks using most of the strategies discussed would be effectively blocked.

Another set of policy decisions that seem likely to emerge relate to the way in which design standards or other elements of professional practice are reviewed and potentially revised. Currently, design standards are often viewed as static parameters in the design process. A more adaptive paradigm implies that design standards will need to change in response to changing risks, which in turn implies that a new *process* for reviewing and updating this information will need to be developed, and that practitioners in each effected sector may need to be involved in this process in a way they have not been historically. As noted in the sections above, if guidelines for professional practice, numerical design standards, etc. are to change, ongoing coordination with existing governing bodies that review these polices and standards will be required. While the need for coordination is clear, from a practical standpoint it is not always entirely clear who (e.g. professional organization, level of government) should take the lead in addressing this issue. Although academic studies can probably help to identify specific areas of concern (as in this paper), practical decisions regarding the review of design standards, developing official decision support products, or other elements of established professional practice will ultimately need to come from practitioners.

Many other federal agencies (e.g. NOAA, FEMA, US Army Corps of Engineers, US Air Force) are also affected by changing risks associated with warming, extreme storms, and flooding and are developing (or in several cases have already convened) task forces to find workable approaches to guide professional practice in the face of changing risks. Leveraging these existing efforts in support of the federal highway system's needs may help reduce costs and improve coordination across various agencies and multiple jurisdictional levels.

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