Western Oregon University – ES476 Hydrology – Winter Term 2018 – Student Poster Project

Water Resources in the Willamette River Basin: Predicted Climate Responses in the 21st Century

Session Chair: Dr. Steve Taylor
Earth and Physical Sciences Department
Western Oregon University
Monmouth, Oregon 97361

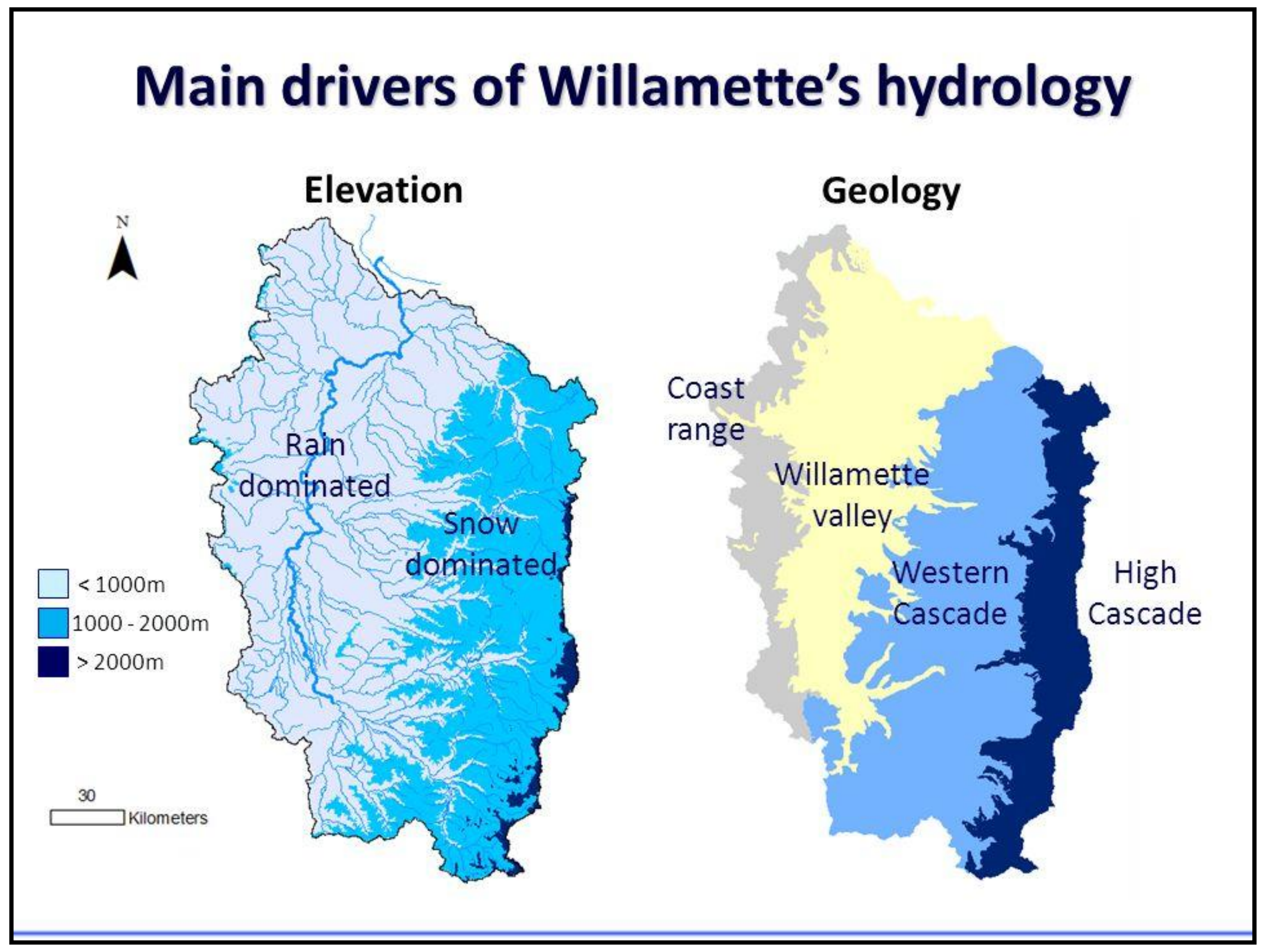
INTRODUCTION

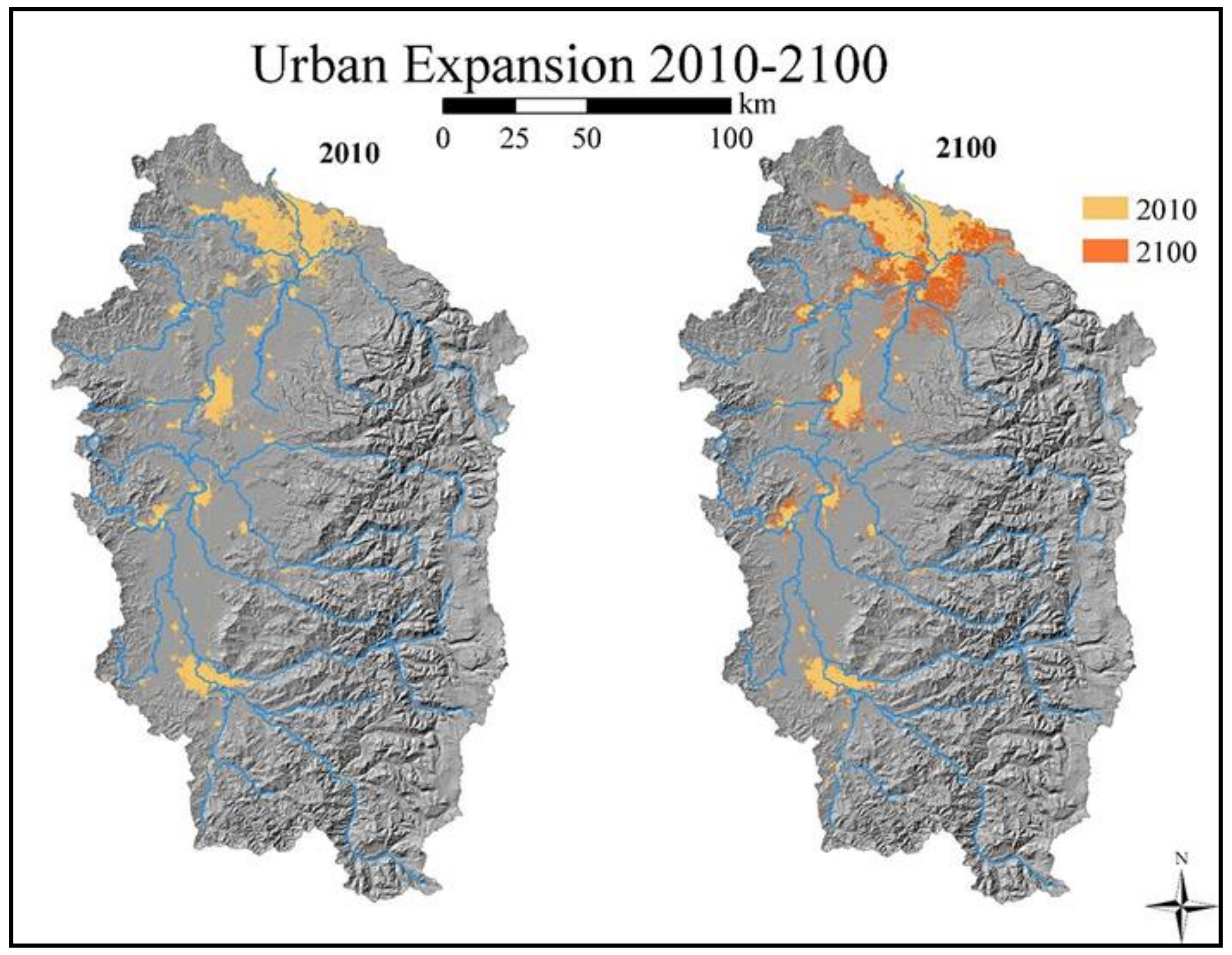
This theme session presents project compilations of students who were enrolled in “ES476 Hydrology”, Winter Term 2018, at Western Oregon University. The focus of the class is study of near-surface hydrologic systems of the Earth. Topics include the hydrologic cycle, water budgets, introductory fluid dynamics, groundwater systems, watershed analysis, water quality and water resource evaluation.

ES476 learning objectives are aligned with WOU Earth Science program outcomes and select components of the LEAP (Liberal Education and America’s Promise; http://aacu.org/leap) learning outcomes developed by the Association of American Colleges and Universities. Upon successful completion of ES476 Hydrology, students will be able to demonstrate minimum competency in the following program areas:

1. Explain mass and energy transfer cycles that drive the hydrologic cycle (PO1).
2. Apply algebraic, trigonometric, and statistical principles to geologic data collection and analysis (Q).
3. Summarize the transfer processes and mass balance functions associated with key components of the global water budget (PO1).

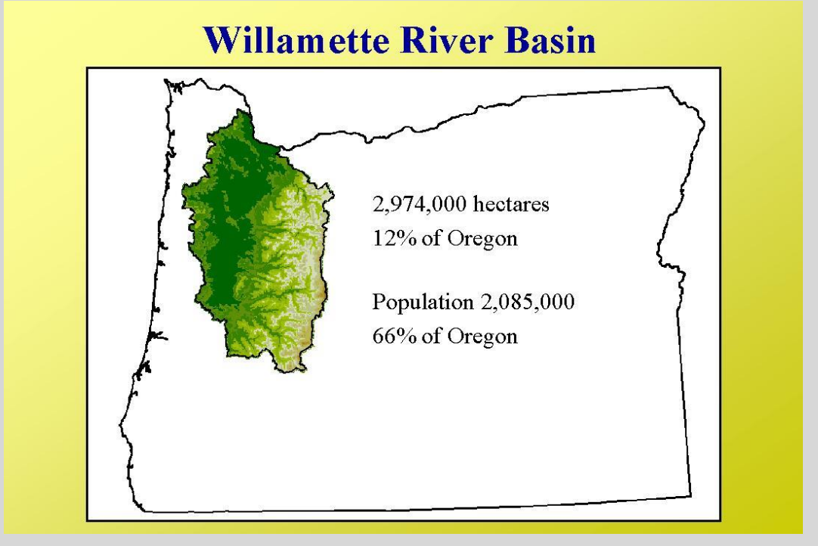
The posters presented in this session are the result of student research on the topic of water resource issues in the Willamette Basin. A review of key publications derived from the Willamette Water 2100 Project; the goal of which is to use an integrated approach to evaluate how climate change, population growth, economic growth, and reservoir operations will change the availability and the use of water in the Willamette River Basin over the 21st century.





Consideration of Climate Change Impacts on Spatial Patterns of Drought Risk in the Willamette River Basin, Oregon, USA

Crystal Harvel, Earth and Physical Sciences Department, Western Oregon University, Monmouth, Oregon, 97361
email: charvel17@wou.edu



INTRODUCTION

When there is a lack in the water cycle it can result in a drought. Droughts can last longer and cover a larger area than other natural disasters. The impacts of droughts are assessed in a couple of different ways, hydroclimatologically , surface water processes, evaporation, groundwater recharge and interception, and runoff. Socioeconomically, no precipitation makes it difficult to water food crops and livestock which causes disruption of agriculture decreasing crop volume and causes price increases food and seeds.

Water sustainability in the Pacific Northwest is an increasing concern. There have been many studies done on precipitation and temperature and their association with runoff trends. However, runoff trends and climatic variables are not always linear. Runoff variability is closely related to climate variability of El Niño Southern Oscillation, ENSO, and Pacific Decadal Oscillation. Climate change could have a seasonal impact on precipitation, temperature, and runoff. If there is a shift in runoff it affects flood control by dams, salmon habitat, energy supply and the demand for water.

GENERAL SETTING

The Willamette River Basin (WRB) is set between the Coast Range on the West and the Western and High Cascade Ranges on the East. Between the two mountain ranges is the Willamette Valley which encompasses most of the agricultural population and industry as well as human population in the Portland Metropolitan area. The WRB is the main water source for wildlife, recreation, industry, agriculture, and human water consumption.

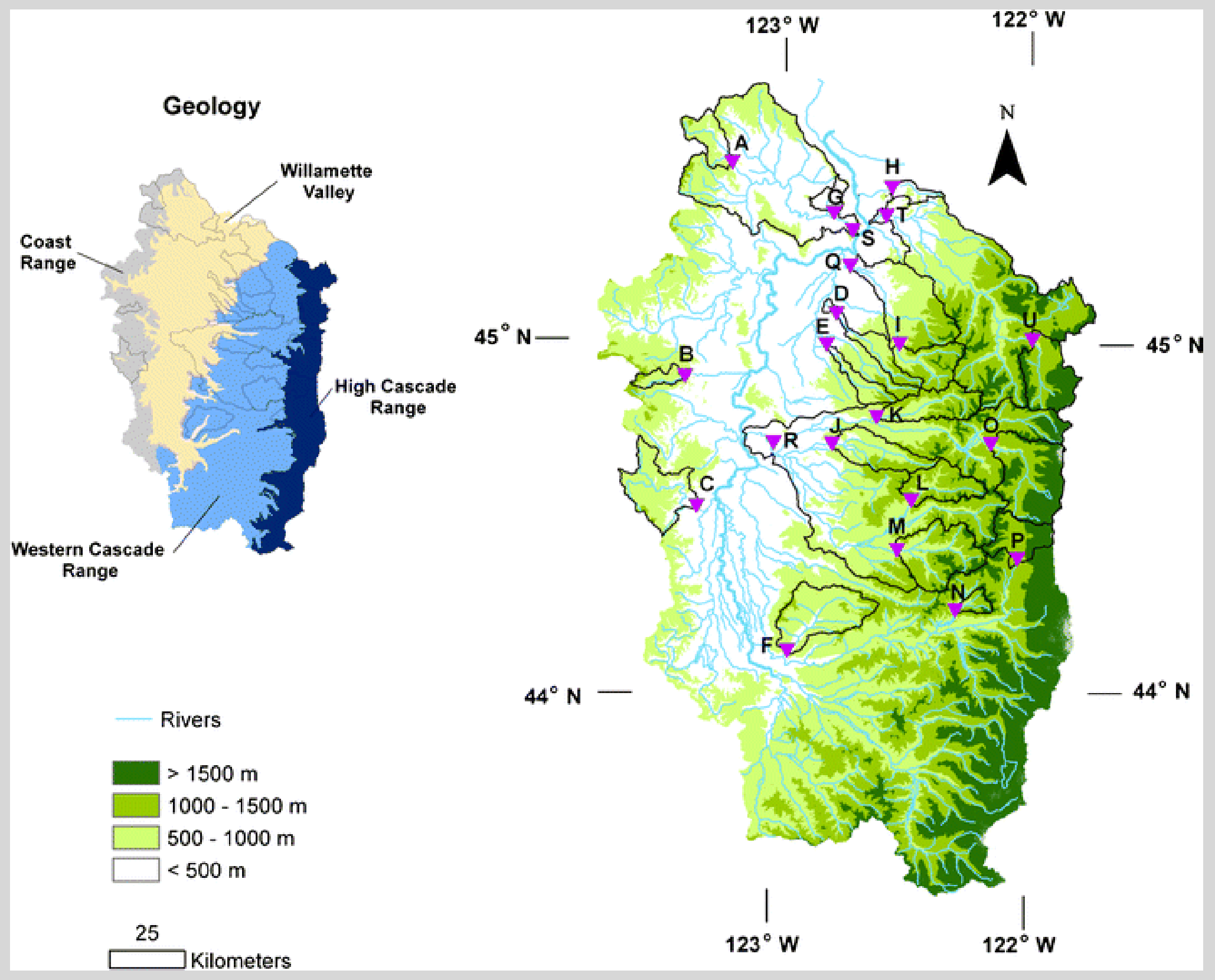


Figure 1. The Willamette River Basin and their geology, elevation, and rivers. The upside-down triangle indicates streamflow gauging stations used to calibrate the PRMS model. The black line shows the watershed boundary

METHODS

The WRB has diverse topography and hydrologic regimes with rainfall and snowfall dominant regions, regimes include: snow basins (>1000m), transient basins (500-1000m), and rain dominant basins (<500m).

The study compiled data from multiple sources of the re-gridded historical climate data, Climate Impact Group (CIG) National Climatic Data Center, COOP Observer, and Environment Canada (EC), to obtain daily climate data of wind speeds, maximum and minimum temperatures and precipitation. It also took topographic characteristics such as soil, slope and elevation into consideration for their spatial parameters (Jung and Chang, 2010) To simulate future hydrologic components such as snow water equivalent (SWE), soil moisture and runoff, actual evapotranspiration, the Precipitation Runoff Modeling System (PRMS), was used to simulate two emission scenarios and eight Global Climate Models (GCM) (Jung and Chang, 2010). Spatial regression models along with the climate change indices were used in the investigation. Streamflow for flow change, and top 5 percentile flow for high flow change. Mann-Kendall (MK) tests determine the trends in these variables which gave the mean values of PRSM simulations. Local Indicators of Spatial Autocorrelation (LISA), observed for "hot" and "cold" clusters of runoff trends by using MK statistics from the WRB.

RESULTS

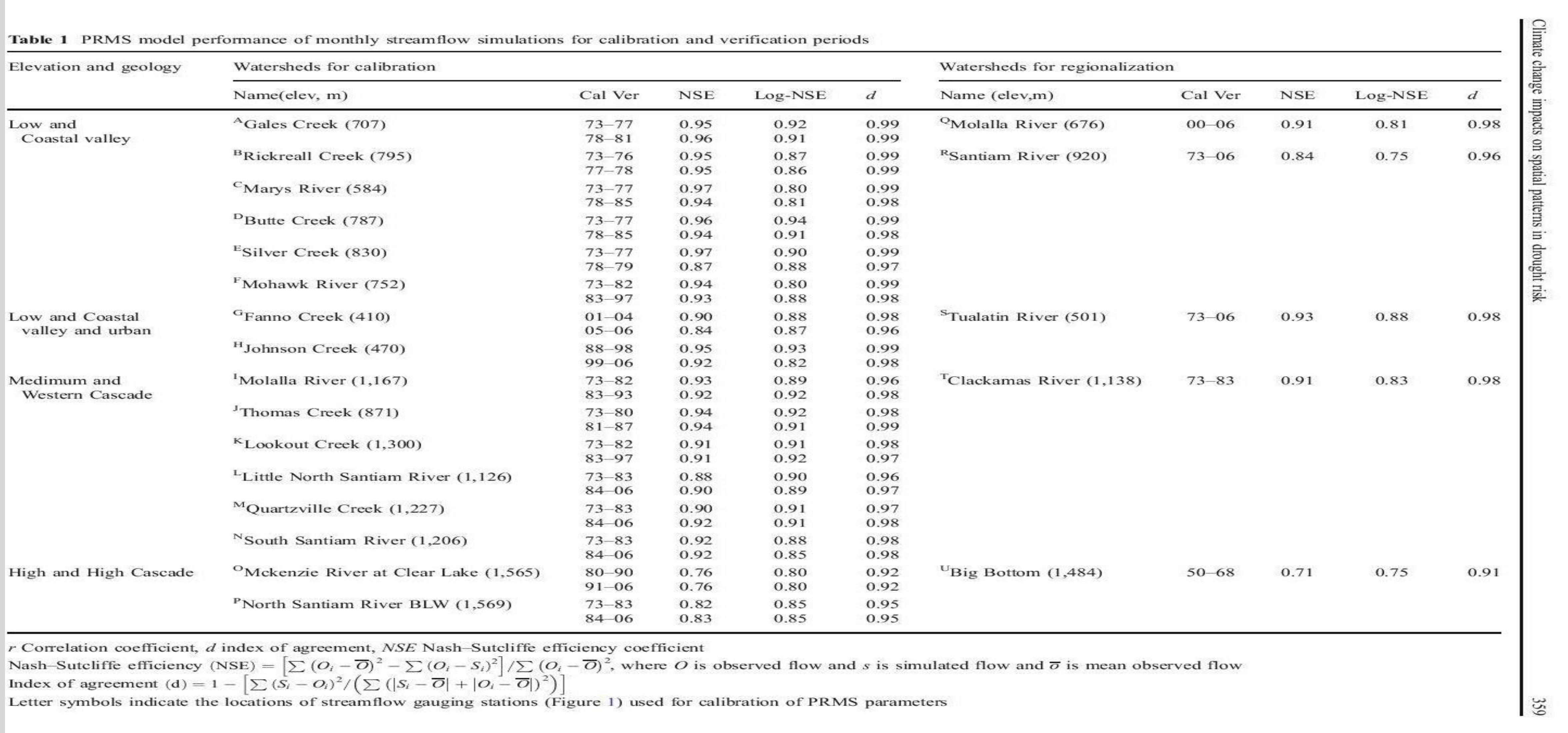


Table 1 PRMS model performance of monthly streamflow simulations for calibration and verification periods

Elevation and geology	Watersheds for calibration: Name(elev, m)	Cal Ver	NSE	Log-NSE	*d*	Watersheds for regionalization: Name (elev,m)	Cal Ver	NSE	Log-NSE	*d*
Low and Coastal valley	[A]Gales Creek (707)	73–77 78–81	0.95 0.96	0.92 0.91	0.99 0.99	[Q]Molalla River (676)	00–06	0.91	0.81	0.98
	[B]Rickreall Creek (795)	73–76 77–78	0.95 0.95	0.87 0.86	0.99 0.99	[R]Santiam River (920)	73–06	0.84	0.75	0.96
	[C]Marys River (584)	73–77 78–85	0.97 0.94	0.80 0.81	0.99 0.98					
	[D]Butte Creek (787)	73–77 78–85	0.96 0.94	0.94 0.91	0.99 0.98					
	[E]Silver Creek (830)	73–77 78–79	0.97 0.87	0.90 0.88	0.99 0.97					
	[F]Mohawk River (752)	73–82 83–97	0.94 0.93	0.80 0.88	0.99 0.98					
Low and Coastal valley and urban	[G]Fanno Creek (410)	01–04 05–06	0.90 0.84	0.88 0.87	0.98 0.96	[S]Tualatin River (501)	73–06	0.93	0.88	0.98
	[H]Johnson Creek (470)	88–98 99–06	0.95 0.92	0.93 0.82	0.99 0.98					
Medimum and Western Cascade	[I]Molalla River (1,167)	73–82 83–93	0.93 0.92	0.89 0.92	0.96 0.98	[T]Clackamas River (1,138)	73–83	0.91	0.83	0.98
	[J]Thomas Creek (871)	73–80 81–87	0.94 0.94	0.92 0.91	0.98 0.99					
	[K]Lookout Creek (1,300)	73–82 83–97	0.91 0.91	0.91 0.92	0.98 0.97					
	[L]Little North Santiam River (1,126)	73–83 84–06	0.88 0.90	0.90 0.89	0.96 0.97					
	[M]Quartzville Creek (1,227)	73–83 84–06	0.90 0.92	0.91 0.91	0.97 0.98					
	[N]South Santiam River (1,206)	73–83 84–06	0.92 0.92	0.88 0.85	0.98 0.98					
High and High Cascade	[O]Mckenzie River at Clear Lake (1,565)	80–90 91–06	0.76 0.76	0.80 0.80	0.92 0.92	[U]Big Bottom (1,484)	50–68	0.71	0.75	0.91
	[P]North Santiam River BLW (1,569)	73–83 84–06	0.82 0.83	0.85 0.85	0.95 0.95					

r Correlation coefficient, *d* index of agreement, *NSE* Nash–Sutcliffe efficiency coefficient

Nash–Sutcliffe efficiency (NSE) $= \left[\sum (O_i - \overline{O})^2 - \sum (O_i - S_i)^2\right] / \sum (O_i - \overline{O})^2$, where O is observed flow and s is simulated flow and $\overline{o}$ is mean observed flow

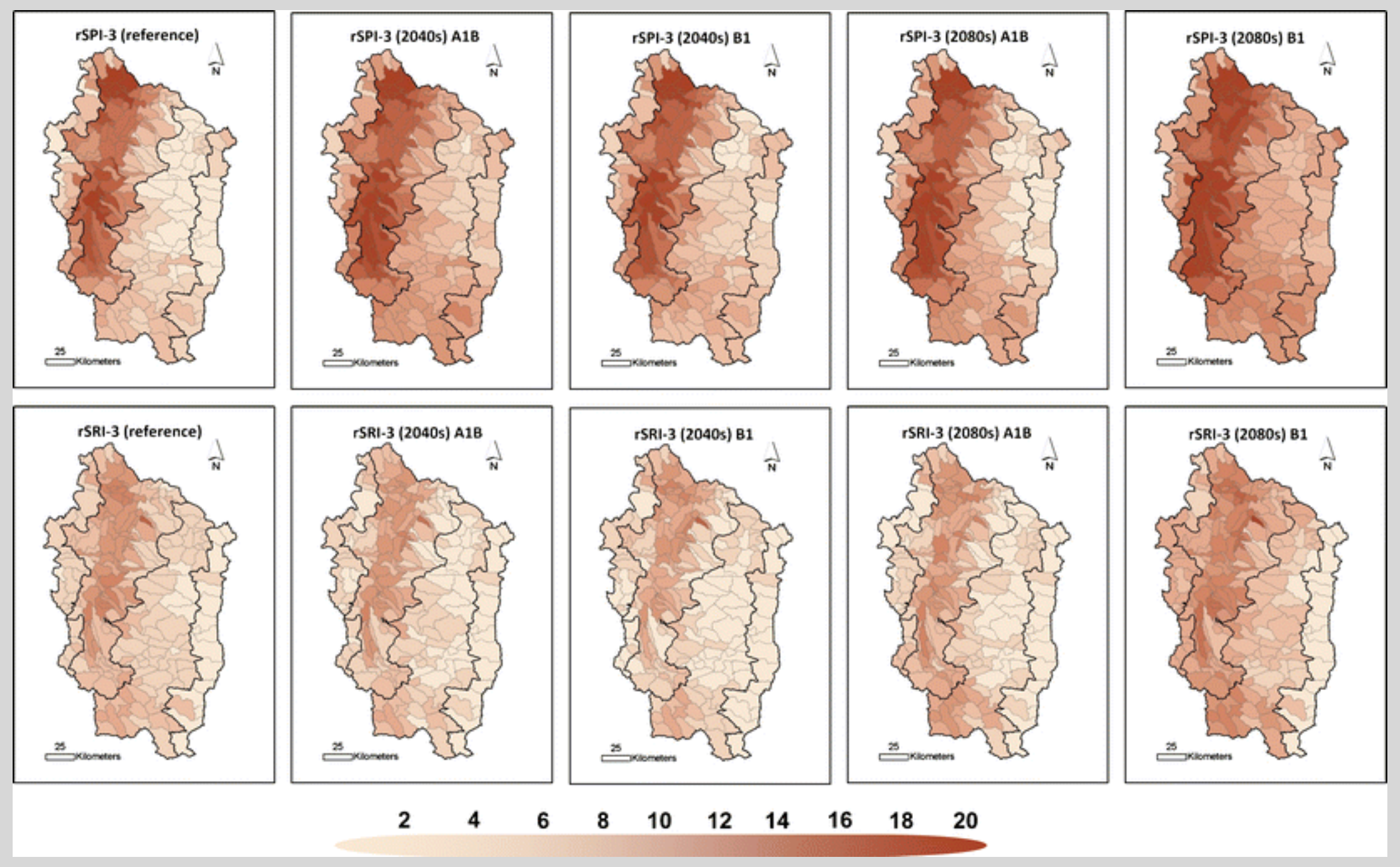
Index of agreement (d) $= 1 - \left[\sum (S_i - O_i)^2 / \left(\sum (|S_i - \overline{O}| + |O_i - \overline{O}|)^2\right)\right]$

Letter symbols indicate the locations of streamflow gauging stations (Figure 1) used for calibration of PRMS parameters

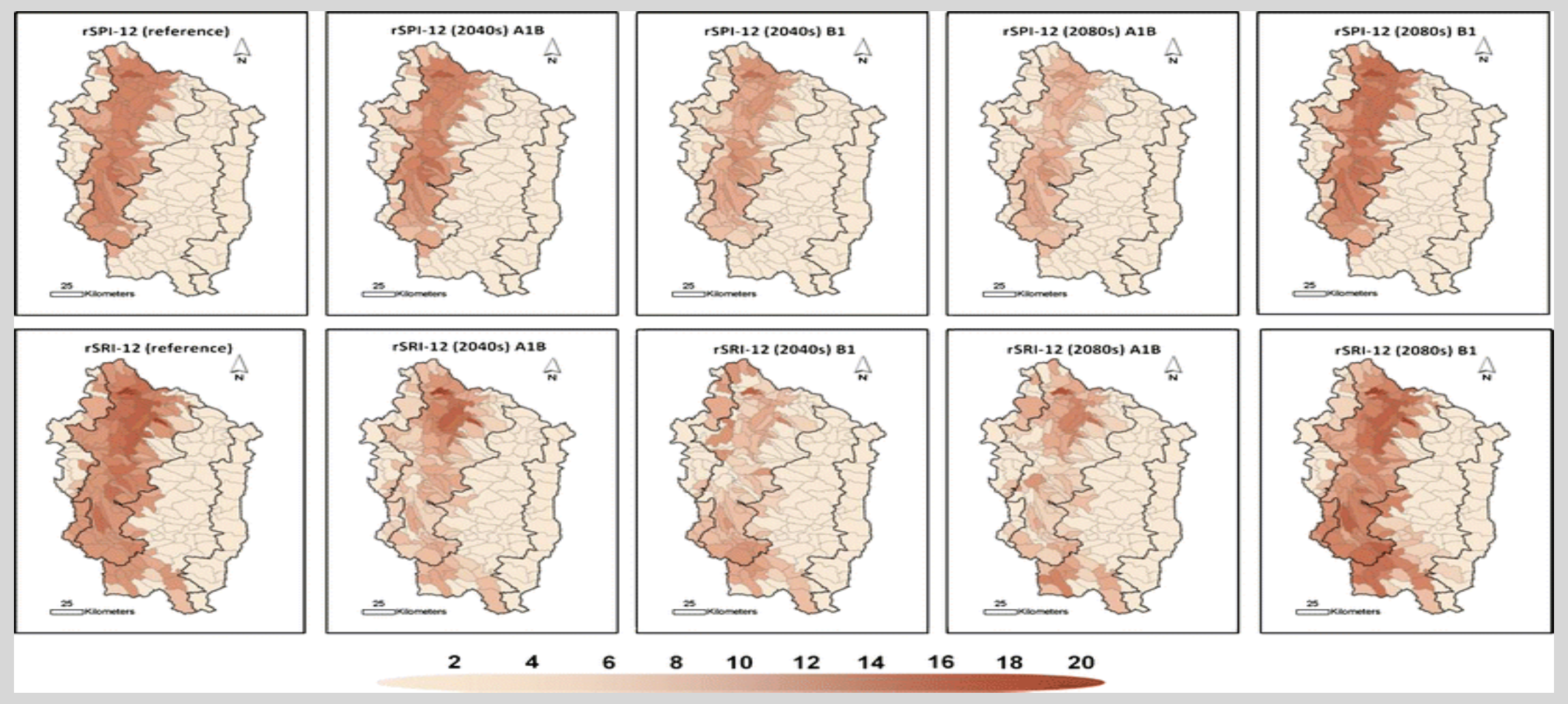
Climate change impacts on spatial patterns in drought risk 359

Using 16 downscaled simulations containing eight GCMs with two GHG scenarios the CIG for the assessment of climate change impacts in the PNW. Special Report on Emissions Scenarios (SRES), A1B and B1 were used for the 21st century climate projection. A1B scenario represents scenario IPCC AR4, medium emissions and B1 scenario IPCC-SRES represents lowest emissions. The two scenarios were subjected to various Greenhouse Gas (GHG) emissions scenarios. A1B and B1 scenarios were until 2050, similar in radiative forcing however, A1B in the later half of the 21st century produced more radiative forcing than that of B1 (Jung and Chang 2010). Bias Correction and Spatial Disaggregation (BCSD), was used for the hydrological application to remove some biases in the regional precipitation and temperature (Wood et al., 2010b).

Through a series of statistical indices, Index of agreement and Nash-Sutcliffe Efficiency (NSE) it was found that an NSE value of 1 was an indicator of a perfect fit with a negative value meaning that simulated values of the hydrological model are not as good of a predictor as an observed flow. The daily values of the NSE Simulated streamflow in the 16 watersheds showed ranges between 0.62 and 0.93 which was an acceptable range. GCM and GHG emission scenario caused large changes in precipitation and temperature, there were consistent changes as well, temperature increases in the summer and winter and decreased precipitation in the summer. A decrease in snowfall and snowpack will impact the summer water supply by reducing the water supply for irrigation, residential and commercial water use. Continued reductions lead to more frequent summer droughts.



Frequency of 3-month drought of rSPI (upper panels) and rSRI (lower panels) for reference, the 2040s, and the 2050s with A1B and B1 GHG emission scenarios.



Frequency of 12-month drought of rSPI (upper panels) and rSRI (lower panels) for the reference, the 2040s, and the 2050s with A1B and B1 GHG emission scenarios.

CONCLUSION

Due to climate change the WRB drought risk is projected to increase. Shifts in flow timing and based on GCMs simulations, a reduction of summer precipitation with short term droughts during growing seasons have affected agricultural productivity. There are several ways to prepare for the changing climate and projected droughts: increasing water storage capacity of existing dams and reservoirs, diversifying water resources sources, drought preparedness, and enhancing irrigation technologies.

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ORIGINAL PAPER

Climate change impacts on spatial patterns in drought risk in the Willamette River Basin, Oregon, USA

Il Won Jung · Heejun Chang

Received: 21 July 2011 / Accepted: 19 September 2011 / Published online: 5 October 2011

Abstract Climate change is likely to lead more frequent droughts in the Pacific Northwest (PNW) of America. Rising air temperature will reduce winter snowfall and increase earlier snowmelt, subsequently reducing summer flows. Longer crop-growing season caused by higher temperatures will lead to increases in evapotranspiration and irrigation water demand, which could exacerbate drought damage. However, the impacts of climate change on drought risk will vary over space and time. Thus, spatially explicit drought assessment can help water resource managers and planners to better cope with risk. This study seeks to identify possible drought-vulnerable regions in the Willamette River Basin of the PNW. In order to estimate drought risk in a spatially explicit way, relative Standardized Precipitation Index (rSPI) and relative Standardized Runoff Index (rSRI) were employed. Statistically downscaled climate simulations forcing two greenhouse gas emission scenarios, A1B and B1, were used to investigate the possible changes in drought frequency with 3-, 6-, 12-, and 24-month time scales. The results of rSPI and rSRI showed an increase in the short-term frequency of drought due to decreases in summer precipitation and snowmelt. However, long-term drought showed no change or a slight decreasing pattern due to increases in winter precipitation and runoff. According to the local index of spatial autocorrelation analysis, the Willamette Valley region was more vulnerable (hot spot) to drought risk than the mountainous regions of the Western Cascades and the High Cascades (cold spot). Although the hydrology of the Western Cascades and the High Cascades will be affected by climate change, these regions will remain relatively water-rich. This suggests that improving the water transfer system could be a reasonable climate adaptation option. Additionally, these results showed that the spatial patterns of drought risk change were affected by drought indices, such that appropriate drought index selection will be important in future studies of climate impacts on spatial drought risk.

I. W. Jung · H. Chang
Department of Geography, Portland State University,
Portland, OR 97201, USA

I. W. Jung · H. Chang (✉)
Institute for Sustainable Solutions, Portland State University,
Portland, OR 97201, USA
e-mail: changh@pdx.edu

1 Introduction

When water becomes scarce in a part of the water cycle, droughts result (Vidal et al. 2010). Given their cumulative nature, droughts occur over larger geographical areas and longer time spans than other natural hazards (e.g., flood, tornado, hurricane, landslide, etc.).The impacts of droughts can be assessed not only hydroclimatologically but also socioeconomically. The socioeconomic damages caused by prolonged or severe droughts are enormous. It is well-known that the dust bowl in the American mid-west in the 1930s precipitated the disruption of agriculture and major human migration to the American west (Greenough et al. 2001). In the globalized modern world, national economies are tightly linked with other nations' economies, and the damage caused by a drought in one region can affect the rest of the world. For example, a recent multi-year drought in southeastern Australia was considered as one of the leading causes of a skyrocketing rise in world's grain prices (Bond et al. 2008; Ummenhofer et al. 2009).

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Irrigation Decisions for Major West Coast Crops: Water Scarcity, Climate Determinants and Costs

Maddie Peterson, Earth and Physical Sciences Dept., Western Oregon University, Monmouth, Oregon, 97361 email: mpeterson17@mail.wou.edu

Introduction

Drought and water scarcity are becoming increasingly major issues for agriculturally significant regions, making irrigation management a necessary step in adapting to water scarcity and climate change. This includes Washington, Oregon, and California agriculture. Extreme weather, physical and economic water shortages, and climate all significantly impact producer's irrigation decisions in all regions (Olen, Wu, Langpap 2015). Producers currently use sprinkler technologies or other methods of water application to mitigate potential crop damage or loss from extreme weather and climate. Analyzing variables of water pricing policies and climate change in the West Coast provides valuable information about the impact of water scarcity on regional agricultural and how irrigational water use in the West Coast can be adapted to better serve the producers of crops. Including how producers would respond to changing water prices, scarcity and climate change without significant production or economic loss.

Agriculture in the West Coast

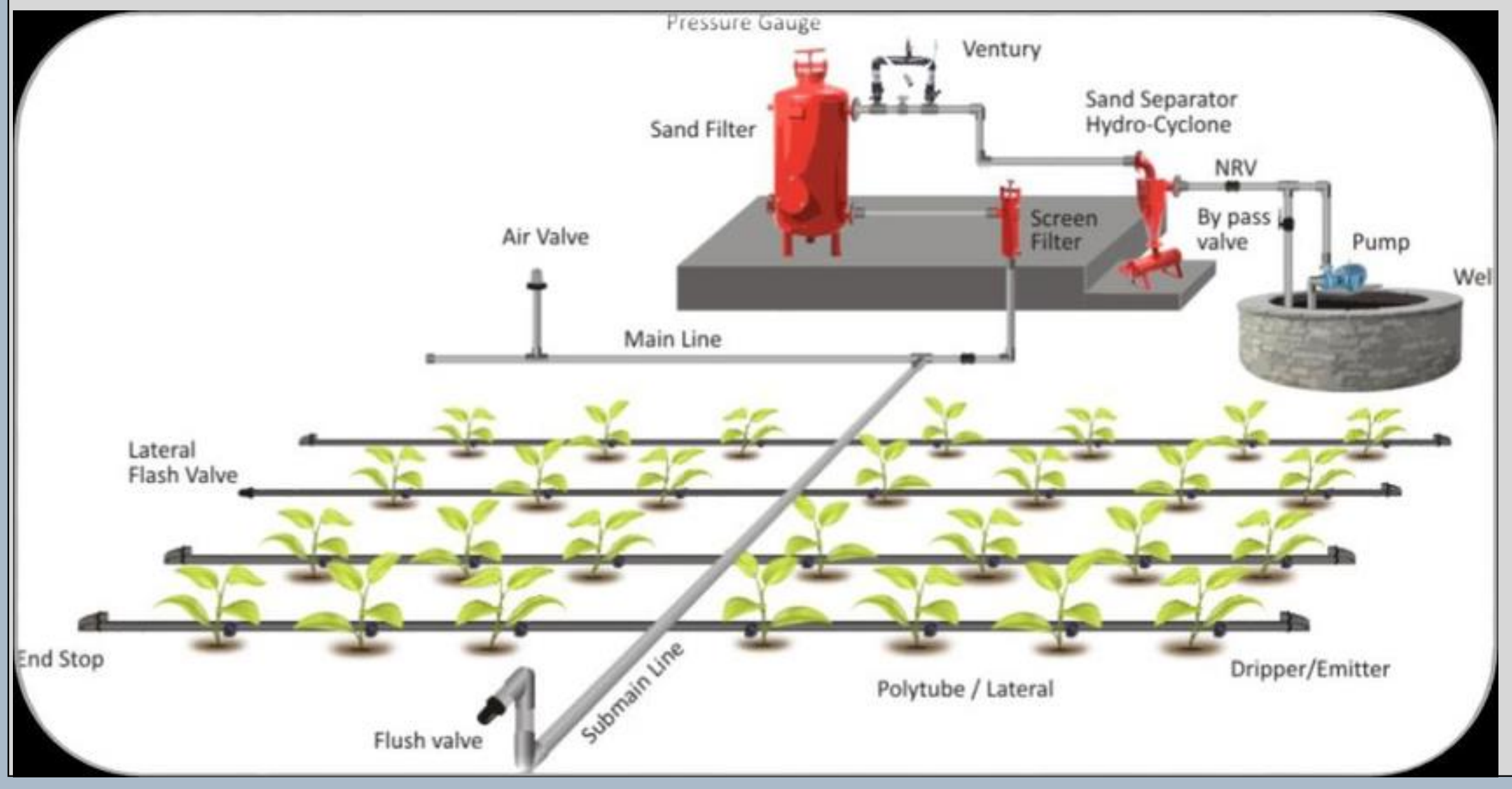
Agriculture accounts for 80% to 90% of total water usage in the West Coast annually (Olen, Wu and Lanpap 2015). Agricultural specifics vary from region to region and state to state, however the entirety of the West Coast is subject to the same issues of increased water scarcity and changing climate, particularly California. Additionally, socioeconomic factors such as population growth and industrialization contribute to water scarcity. In the West Coast, a variety of specialty and forage crops are grown including wheat, alfalfa and soybeans, as well as extensive orchard and vineyard production. How producers modify irrigation practices in response to climate and water resource issues differ due to a host of variables. Individual crops require different water application rates and technology adoption, with some less responsive to water saving application rates than others, such as orchards. Whether a producer receives water resources from a federal source also affects rates of water application, with those who do less likely to use water saving methods for crops as well as having higher mean water application rates per crop (Olen, Wu and Langpap 2015). Due to the significance of agricultural production in the West Coast, it is economically and socially necessary to consider the future of water resource management in agriculture and how that impacts the surrounding regions.

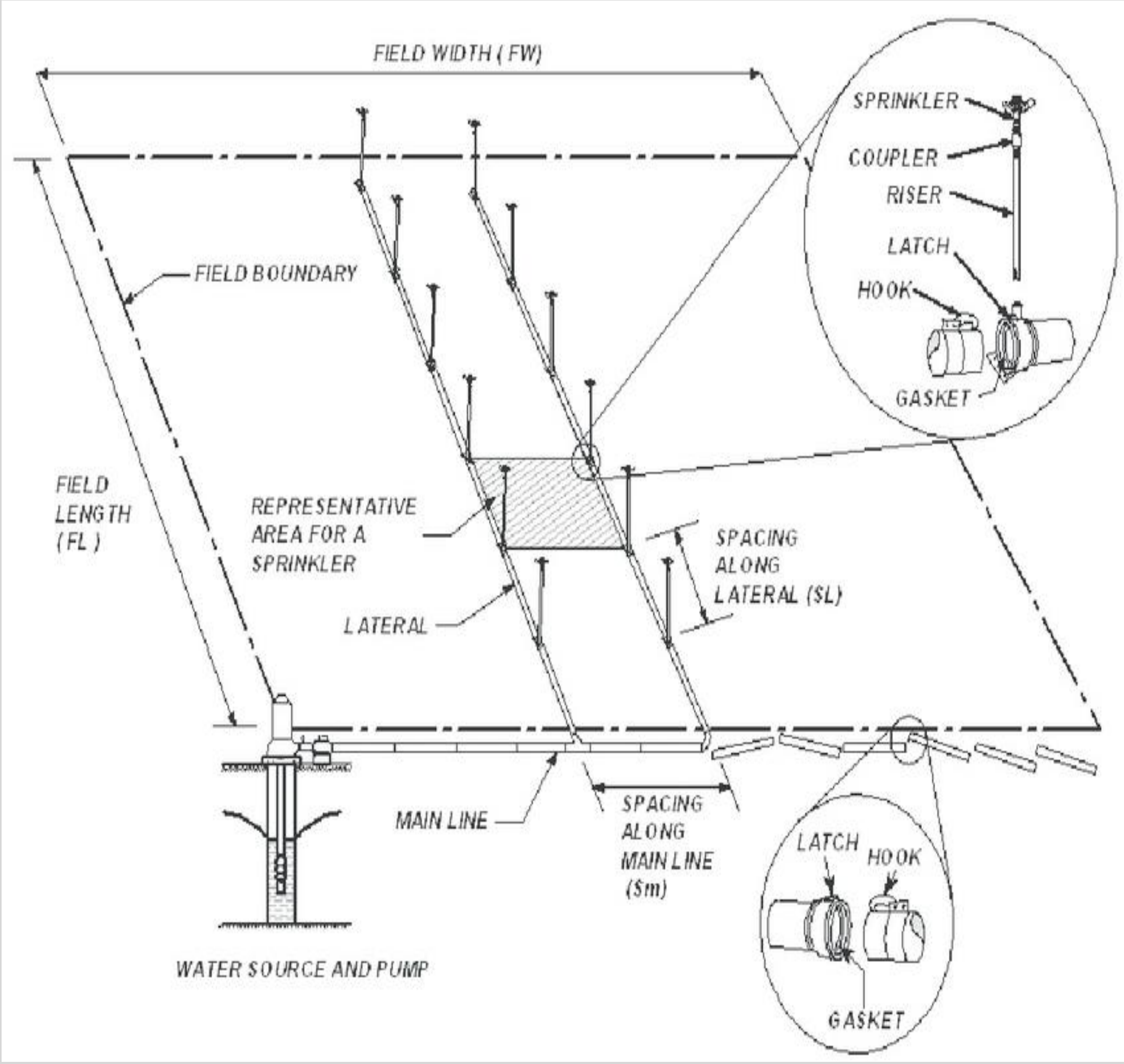
Methodology

Data analyzed and modeled from the 2007 Farm and Ranch Irrigation Survey database (FRIS) and from the U.S Department of Agriculture provides the most complete irrigation management model for major crops in the regions of Washington, Oregon, and California while accounting for the largest quantity of variables (Olen, Wu, and Langpap 2015). Equations that represent usage per individual farms water shares, as well as the individual crop categories in respect to adopted technology and water application rates were utilized. Sprinkler technology and water application rates also influence irrigation decisions. The effects of water scarcity on irrigation choices also depends on the crop grown, which includes energy prices and acreage allocation. Climate and extreme weather events (including droughts, temperature extremes and frost) are expected to increase in frequency and scale with each passing year. Snowpack melt is also predicted to increase, heightening the dry seasons further. All of these climate variables impact producers irrigation decisions. Socioeconomic factors must be considered in addition to environmental ones; increasing demand for water by urban populations, coupled with the difficulty of developing new water supplies, is forcing farmers in the West Coast to cope with reduced access to surface water (Sunding 2002). The cost of improving water access depends vitally on how the reductions are allocated among users. This requires further methodology that measures the impacts of water supply policy changes on irrigated agriculture to understand how reforms would impact producers.

Results

A number of technologies are employed to mitigate water scarcity and climate issues, with degrees of effectiveness depending upon the compatibility of the crop with the irrigation technology. Some examples include sprinkler systems (Figure 1) and drip systems (Figure 2). Effectiveness of water saving applications depends upon the crop grown, the size of growing area, and the amount of water consumed by a crop, all of which are affected by climate and weather events, while the risk of damage by extreme weather and climate depend upon the type of crop. However, water saving application methods are not effective for orchards and vineyards, due to the groundwater well depth needed to effectively irrigate them. Producers who grow multiple crops who experience a diversity of extreme weather, are limited in what technology they can adopt. This has important policy consequences, as water pricing policies are advocated as a means of adopting water saving irrigation technology. It is noted that in some cases this would actually cost producers. While drip irrigation is the most effective water saving irrigation method, sprinklers are the necessary choice, for example, it is widely used in areas of California to prevent frost damage to large vineyards. In that case, producers would not adopt the most cost effective method (drip) and imposing water policy pricings would actually increase costs for producers.





Outside supply institutions that control and supply water also influence irrigation decisions for crop producers. Those who receive water from federal agencies are less likely to implement more water saving irrigation methods for crops, and have higher mean water application rates than those who do not receive surface water from federal sources. Water application rates are more responsive to surface water costs if the water cost per unit area is lower. Surface water cost per unit is reduced for producers paying a fee for surface water or those using a surface water supply only (Olen, Wu and Langpap).

Discussion

The research suggests that incentive structures, which encourage adoption of water saving technologies, will not actually reduce agricultural water use because the water savings could be used to further expand cropland (Olen, Wu, and Langpap 2015). Significant changes in well depth would be needed to create economically significant changes in irrigation decisions. Irrigation decisions are more responsive to temperature than precipitation, meaning producers respond vastly differently to climate change by region. Lastly, improved groundwater regulation would provide the signal to producers to adopt methods of irrigation that conserve water resources, which a version of has been implemented in California under the Sustainable Groundwater Management Act of 2014 (Sunding 2002). The results of this study provide information needed for developing future water pricing policies and groundwater regulations. The research provides detailed information about how producers might respond and subsequently adapt to shifting climate and variability in the agricultural industry in the West Coast.

Conclusions and Summary

Rising temperatures and decreasing and shifting precipitation patterns are predicted to impact both the production and quality of agricultural commodities in the West Coast with each passing year. As well as increased occurrence of extreme weather events over time. Producers have options for water saving irrigation methods available, and effectiveness depends upon a number of crop and weather variables. Water saving irrigation also depends upon water pricing policies by region and supplies of surface water from federal agencies. The ultimate goal of this research into water scarcity and its associated factors is to provide a model as to how crop producers, government agencies and municipal bodies in the region may respond and adapt to changing climate and water pricing policies in the future.

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IRRIGATION DECISIONS FOR MAJOR WEST COAST CROPS: WATER SCARCITY AND CLIMATIC DETERMINANTS

BEAU OLEN, JUNJIE WU, AND CHRISTIAN LANGPAP

This article uses the 2007 Farm and Ranch Irrigation Survey database developed by the U.S. Department of Agriculture to assess the impact of water scarcity and climate on irrigation decisions for producers of specialty crops, wheat, and forage crops. We estimate an irrigation management model for major crops in the West Coast (California, Oregon, and Washington), which includes a farm-level equation of irrigated share and crop-specific equations of technology adoption and water application rate (orchard/vineyard, vegetable, wheat, alfalfa, hay, and pasture). We find that economic and physical water scarcity, climate, and extreme weather, such as frost, extreme heat, and drought, significantly impact producers' irrigation decisions. Producers use sprinkler technologies or additional water applications to mitigate risk of crop damage from extreme weather. Water application rates are least responsive to surface water cost or groundwater well depth for producers of orchard/vineyard. Water supply institutions influence producers' irrigation decisions. Producers who receive water from federal agencies use higher water application rates and are less likely to adopt water-saving irrigation technologies for some crops. Institutional arrangements, including access to distinct water sources (surface or ground) and whether surface water cost is fee based, also affect the responsiveness of water application rates to changes in surface water cost. The analysis provides valuable information about how producers in irrigated agricultural production systems would respond and adapt to water pricing policies and climate change.

Key words: Irrigation decisions, water scarcity, climate heterogeneity, extreme weather, water pricing policies.

JEL codes: Q12, Q15, Q54, Q18, Q16.

Rising temperatures and shifting precipitation patterns are expected to impact the yield and quality of agricultural commodities in the West Coast (Adams, Wu, and Houston 2001). Damaging frost events are expected to persist in the future (Rigby and Porporato 2008), while extreme heat and drought events are expected to affect larger areas and become more frequent and severe in the West Coast (Jackson et al. 2011). Climate change is also anticipated to accelerate snowmelt in West Coast mountain ranges, which would intensify dry-season water scarcity (Hayhoe et al. 2004).[1] Growth in populations and income and pressure to increase biological streamflows will also intensify water scarcity in the West Coast (Burke, Adams, and Wallender 2004; Kummu et al. 2010).

Beau Olen is faculty research assistant, JunJie Wu is Emery N. Castle Chair, and Christine Langpap is associate professor, Department of Applied Economics, Oregon State University, Corvallis, OR 97331-3601. The authors thank Chris Mertz, Director of the USDA National Agricultural Statistic Service's Pacific Northwest Regional Office, for providing access to the FRIS data used in this article. They acknowledge useful comments obtained from presentations at Oregon State University and the Agricultural and Applied Economics Association 2012 Annual Meeting in Seattle, WA. They also appreciate helpful comments provided by Eric C. Schuck and Richard M. Adams. Lastly, they thank two anonymous referees for their comments.

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[1] Accelerating snowmelt intensifies dry-season water scarcity for two reasons (Hayhoe et al. 2004): (1) dry-season streamflows are diminished, which reduces water available for diversion and increases salt water intrusion to river systems, and (2) wet-season streamflows are increased and therefore reservoir 'rule curves' may mandate the release of water that is stored for dry-season uses to hedge against winter flood risk.

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Western Oregon University
Geology & Earth Science

Snow and the Fire Cycle in Western Oregon

Walter Schoen, Earth and Physical Sciences Department, Western Oregon University, Monmouth, Oregon, 97361
Email: wschoen14@mail.wou.edu

Abstract

Evidence has been documented of increasingly warmer temperatures through gaging stations around the United States. Increasing temperatures makes the probability of forest fires far more likely. A study has shown that each year, the United States forest fire occurrence rate increases by around 7 per year (Dennison, 1984-2011).Large forests near mountainous regions in particular are susceptible to climate change. Forest like these are susceptible since most of the water they receive is derived from snow melt. Snow is affected by climate change but another contributing factor of snowpack is its albedo. The albedo, or ability snow has to reflect solar radiation, is affected by forest fires declining whenever there is a blaze close to the snow. This was determined by measuring and comparing the reflectivity of areas with snow that had a fire, to those that hadn't been burned. Areas with low albedo melt faster and with a quickly dwindling snowpack and many areas will experience drought in the later months raising the probability of another fire.

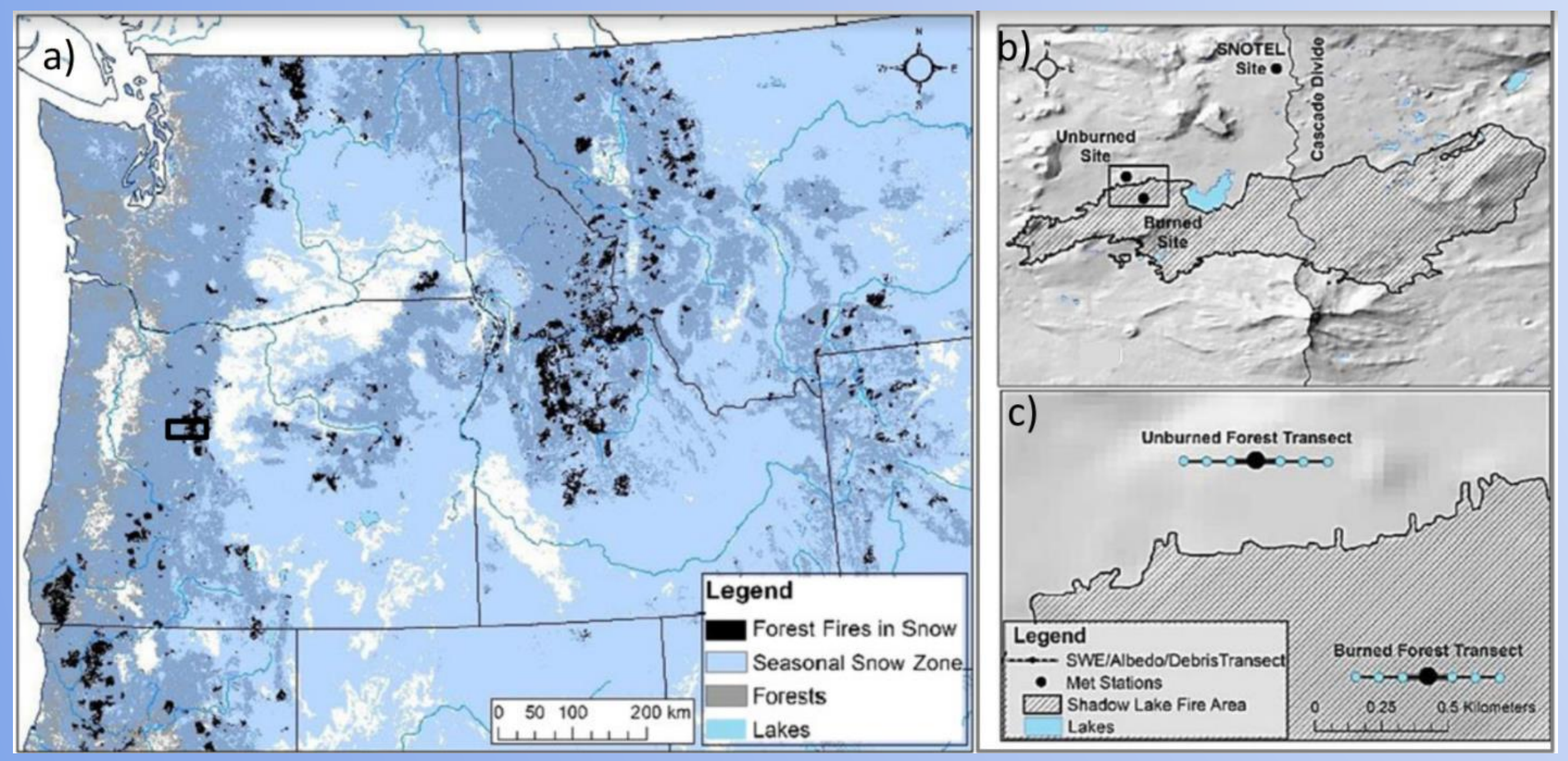


FIGURE 1.

Introduction

The Oregon Cascades, where a deep snowpack occurs, is the site used to study because large scale forest fires have occured. Researchers used a variety of methods in order to connect burned areas with higher albedo rates. Evidence was found that shows that snow albedo is a major driver of ablation in both burned and unburned zones. The Albedo was found to strongly correlate to days since snowfall and surface debris concentrations (Gleason, 2016). Our study area (fig 1) which is at an elevation of 1450m contains both burned and unburned forested area and the border in between. Over a period of 3 years information was collected about the albedo in these two areas in association with surface debris measurements.

Research Methods

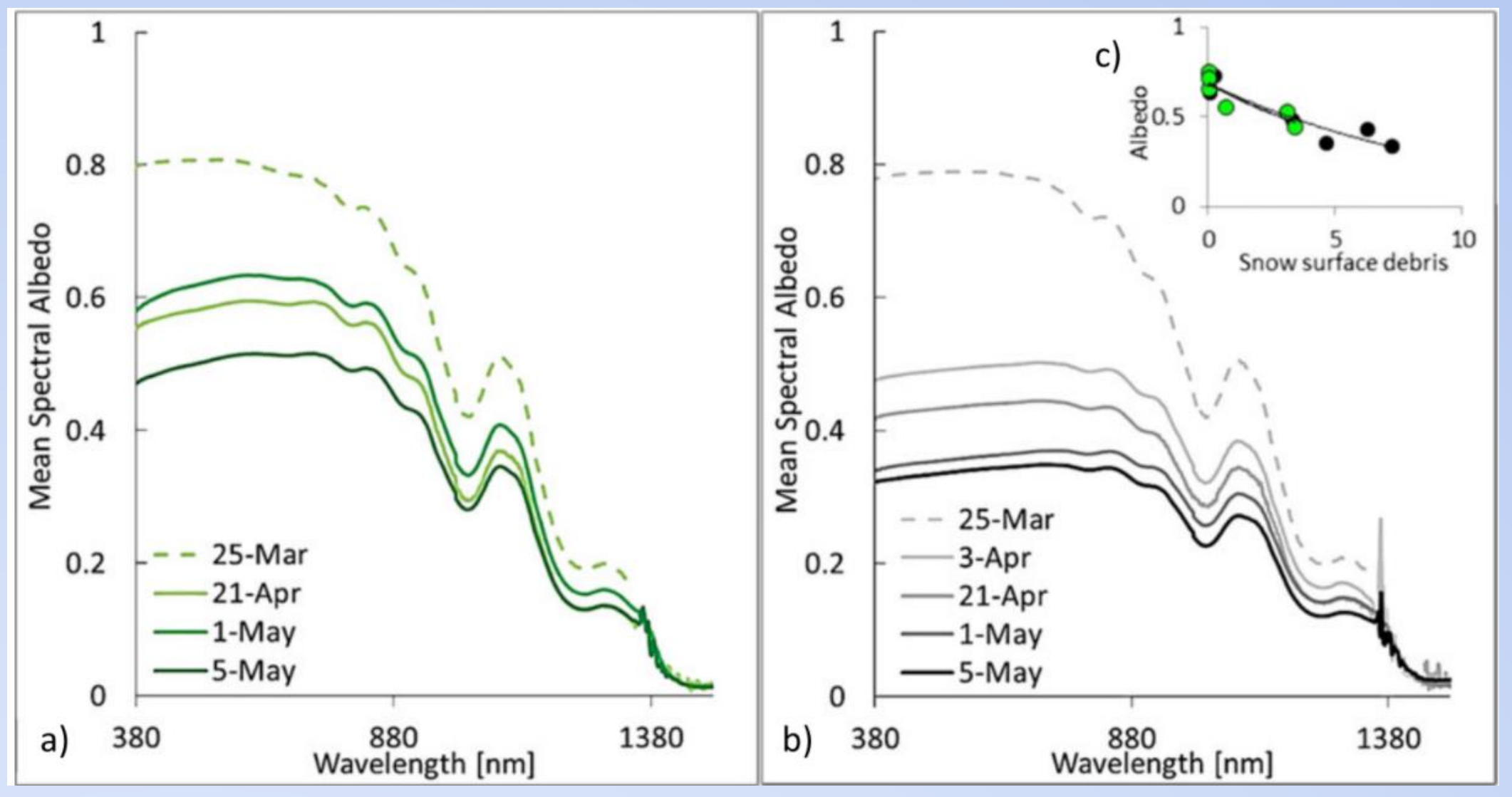


FIGURE 2.

Researchers used a unique variety of tools in order to make field measurements. Measurements like these are necessary in order to characterize snow albedo decay and model its patterns. Tools like the Analytical Spectral Devices Full-Range Portable Field Spectroradiometer which allowed the researchers to measures up to 1 nanometer spectral resolution of light. The field was divided into 20 m sections along a 200 m transect through the area (Gleason, 2016). Each year many measurements were made during the times of accumulation and ablation of the snow. Along each course the snow depth and surface debris concentrations were recorded on a monthly basis and every 2 weeks during ablation and accumulation. Figure 2 shows a simplified version of their snowpack thickness results showing the pack diminishing from .3 to .1 in similar areas and Figure 3 looks closely at the accumulation and ablation data.

Site	Year	Date of peak SWE	Peak SWE (cm)
Unburned forest	WY2012	02 Apr	90
	WY2013	01 Mar	77
	WY2014	30 Mar	59
	All years		
Burned forest	WY2012	15 Apr	101
	WY2013	01 Mar	61
	WY2014	03 Mar	35
	All years		

FIGURE 3.

Fire Cycle

A pattern can be drawn between forest fires, Albedo decay, and the increasing number of forest fires in America. Figure 3 shows forest fires in America are increasing by around 7 per year (Dennison, 1984-2011). When forest fires occur in mountain areas they increase the melting rate of snow. When snowpack melts early it is known that drought follows as the water from some rivers dry up. Droughts like these effect any surrounding forests that haven't been burned drying them up and increasing the probability that a forest fire can start and spread. A cyclical pattern can be seen as the fires cause snow to melt early, which cause drought, which dry out forests leading to more fires.

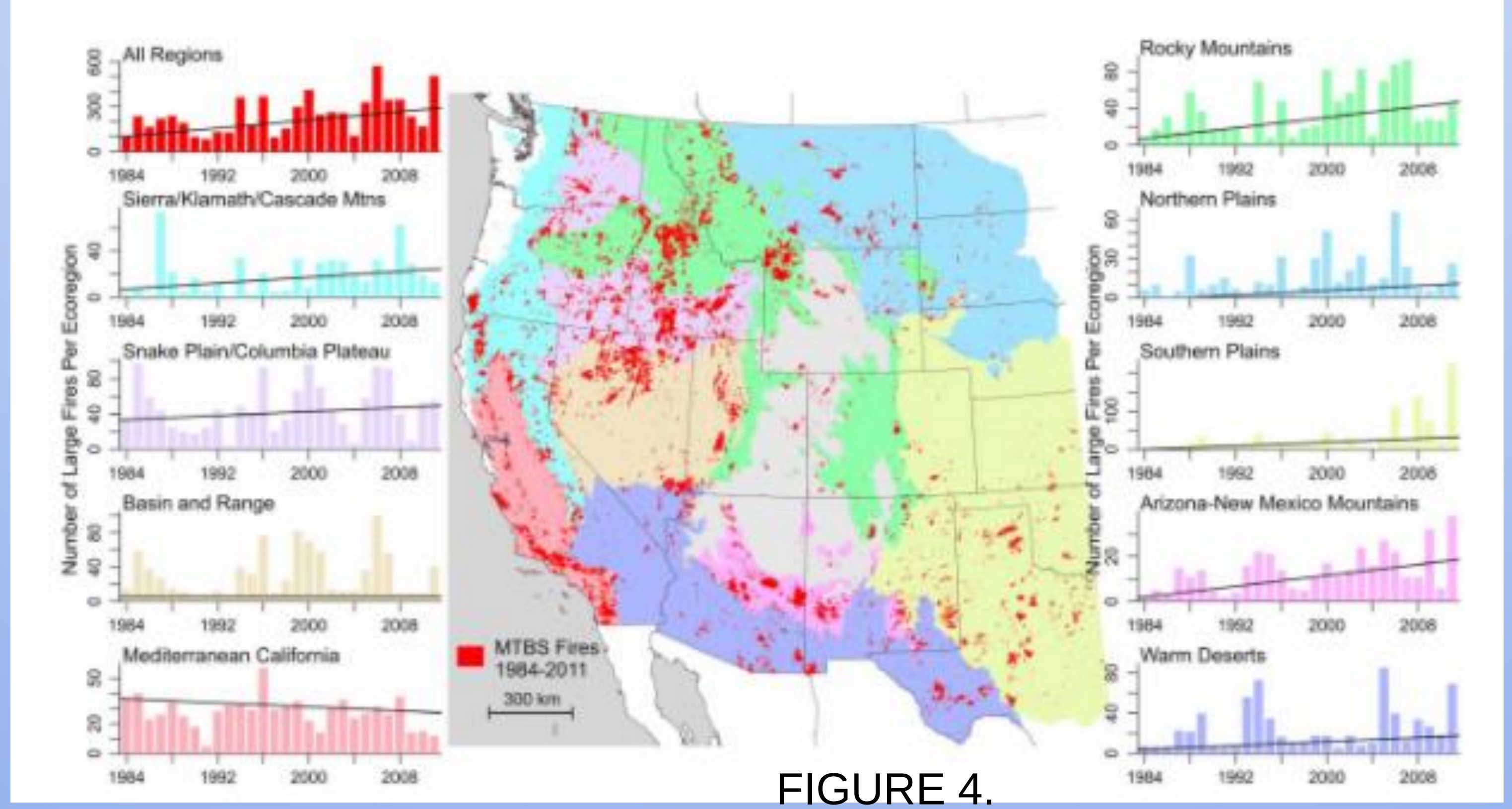
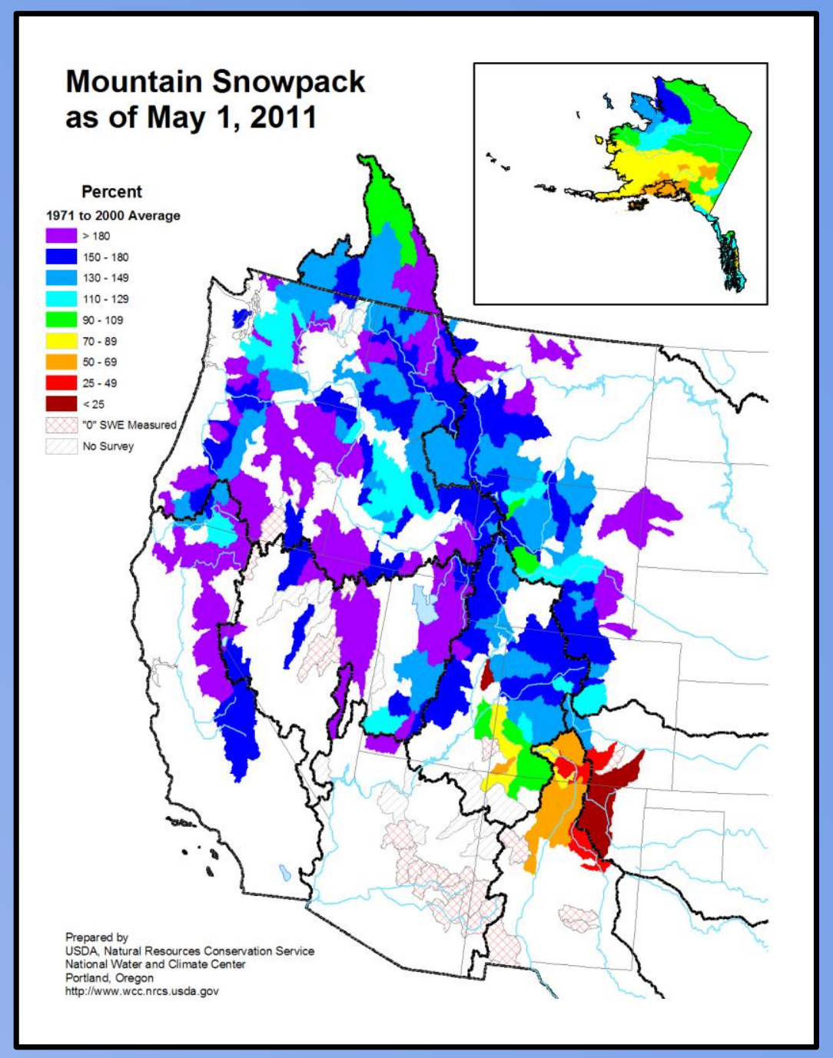


FIGURE 4.



Conclusion

Areas with snowpack are delicate environments that three years following a forest fire see higher melting. This melting was analysed, mapped, and modeled using many different methods to reveal that radiation in burned areas is more easily trapped. This albedo decay caused melting is caused by albedo decay in the snow caused by the dark ashy soil trapping solar radiation causing the snow to melt earlier in the year. Gleason (2016) suggested that the annual fire occurrence is increasing by a rate of around 7 large fires combined per year. This fire occurrence is predicted to worsen in coming years due to drought caused by early mountain snowpack melting. If multiple drought occurrence increase the likelihood for large fires we will see more fires and droughts in the days to come.

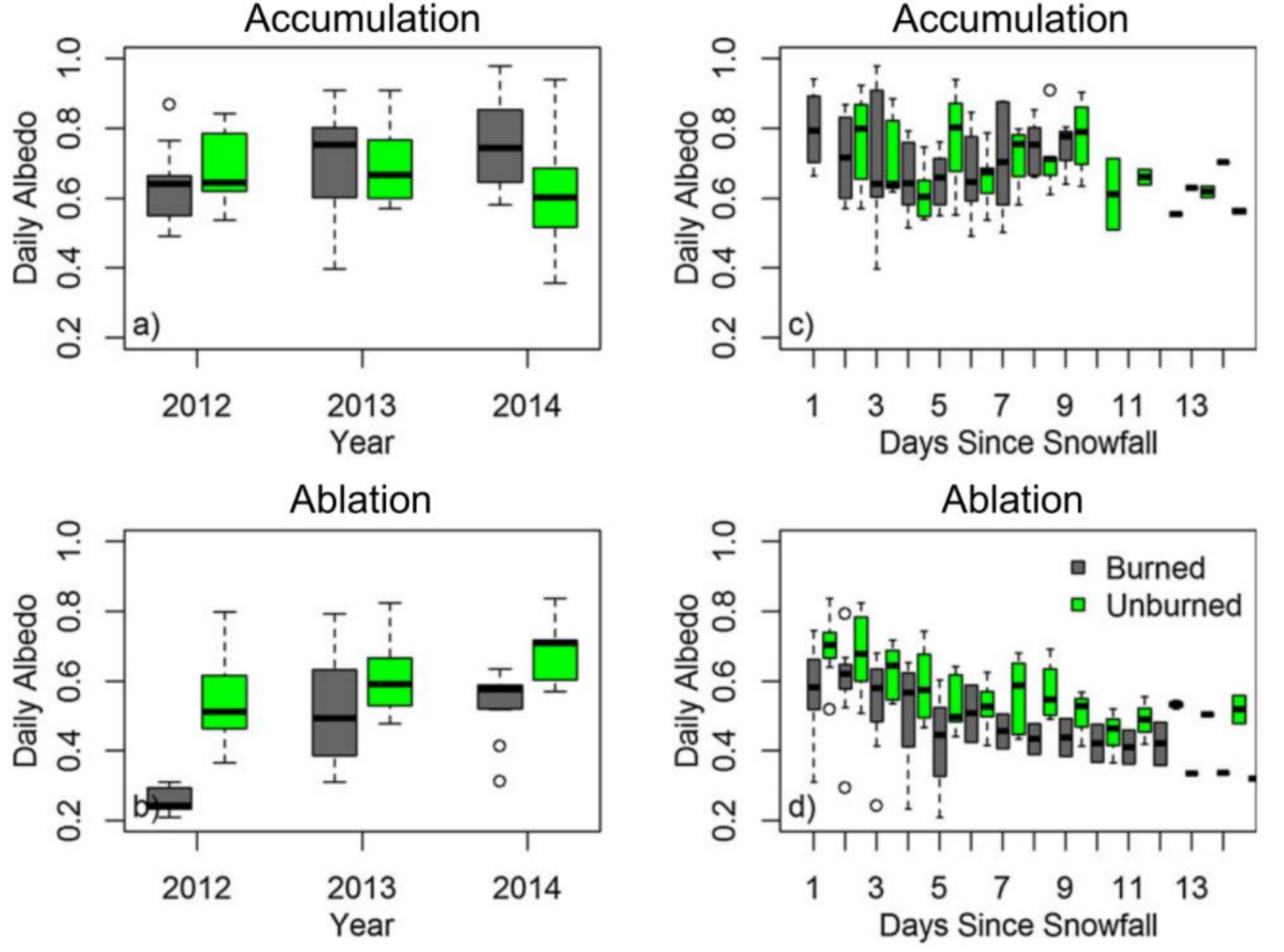


FIGURE 5.

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- Gleason, Kelly E., Nolin, Anne W., 2016, Charred forests accelerate snow albedo decay: parameterizing the post-fire radiative forcing on snow for three years following fire, Wiley Online Library, 3855-3870

HYDROLOGICAL PROCESSES
Hydrol. Process. **30**, 3855–3870 (2016)

(wileyonlinelibrary.com) DOI: 10.1002/hyp.10897

Charred forests accelerate snow albedo decay: parameterizing the post-fire radiative forcing on snow for three years following fire

Kelly E. Gleason* and Anne W. Nolin

College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR, 97331, USA

Abstract:

As large, high-severity forest fires increase and snowpacks become more vulnerable to climate change across the western USA, it is important to understand post-fire disturbance impacts on snow hydrology. Here, we examine, quantify, parameterize, model, and assess the post-fire radiative forcing effects on snow to improve hydrologic modelling of snow-dominated watersheds having experienced severe forest fires. Following a 2011 high-severity forest fire in the Oregon Cascades, we measured snow albedo, monitored snow, and micrometeorological conditions, sampled snow surface debris, and modelled snowpack energy and mass balance in adjacent burned forest (BF) and unburned forest sites. For three winters following the fire, charred debris in the BF reduced snow albedo, accelerated snow albedo decay, and increased snowmelt rates thereby advancing the date of snow disappearance compared with the unburned forest. We demonstrate a new parameterization of post-fire snow albedo as a function of days-since-snowfall and net snowpack energy balance using an empirically based exponential decay function. Incorporating our new post-fire snow albedo decay parameterization in a spatially distributed energy and mass balance snow model, we show significantly improved predictions of snow cover duration and spatial variability of snow water equivalent across the BF, particularly during the late snowmelt period. Field measurements, snow model results, and remote sensing data demonstrate that charred forests increase the radiative forcing to snow and advance the timing of snow disappearance for several years following fire.

KEY WORDS snow albedo; forest fire; snowmelt; snowpack energy balance; snowpack radiative forcing; snow ablation

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INTRODUCTION

In response to warmer temperatures and declining snowpacks, large wildfires are increasing in frequency, intensity, and extent across the western USA (Westerling *et al*., 2006, 2011; Trouet *et al*., 2010; Semmens and Ramage, 2012). In turn, forest fire disturbance affects patterns of snow accumulation and ablation by reducing canopy interception, increasing turbulent fluxes, and modifying the net radiation balance (Liu *et al*., 2005; Winkler *et al*., 2005; Boon, 2009; Burles and Boon, 2011; Gleason *et al*., 2013; Ueyama *et al*., 2014).

Forest fire disturbance significantly alters the net radiation balance of the underlying snowpack by increasing the transmission of incoming solar radiation through the canopy, decreasing the emission of longwave radiation by the canopy, and decreasing snow surface shortwave albedo (integrated across the spectral range of 0.3–3.0 μm) by deposition of organic debris from the canopy (Pomeroy and Dion, 1996; Winkler *et al*., 2010; Burles and Boon, 2011; Gleason *et al*., 2013). Charred forests increase the rate of snowmelt leading to earlier snow disappearance (Winkler *et al*., 2010; Gleason *et al*., 2013; Harpold *et al*., 2014; Micheletty *et al*., 2014), which amplifies land surface–atmosphere radiative feedback and alters terrestrial–atmosphere hydrological interactions (Liu *et al*., 2005; Dery and Brown, 2007; O'Halloran *et al*., 2012; Ueyama *et al*., 2014).

Although forest fire disturbance is extensive in the snow-dominated headwaters of most western USA watersheds (Gleason *et al*., 2013) and such disturbance is projected to increase across the western USA (Moritz *et al*., 2012; Abatzoglou and Kolden, 2013; Dennison *et al*., 2014), forest fire impacts on snow accumulation and snowmelt patterns are still poorly understood and only rarely considered in snow hydrology (Lanini *et al*., 2009).

This study utilizes a unique dataset to evaluate forest fire disturbance effects to snow albedo decay for three

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*Correspondence to: Kelly E. Gleason, Oregon State University, College of Earth, Ocean and Atmospheric Sciences, Corvallis, Oregon 97331, USA.
E-mail: kgleason@usgs.gov

Western Oregon
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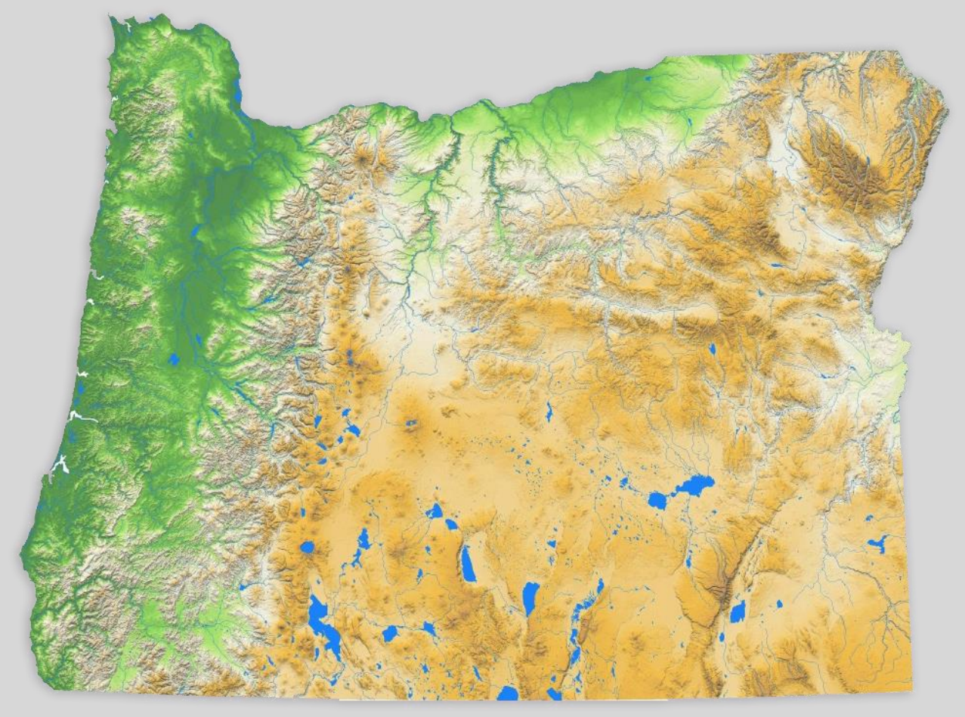
Earth Science

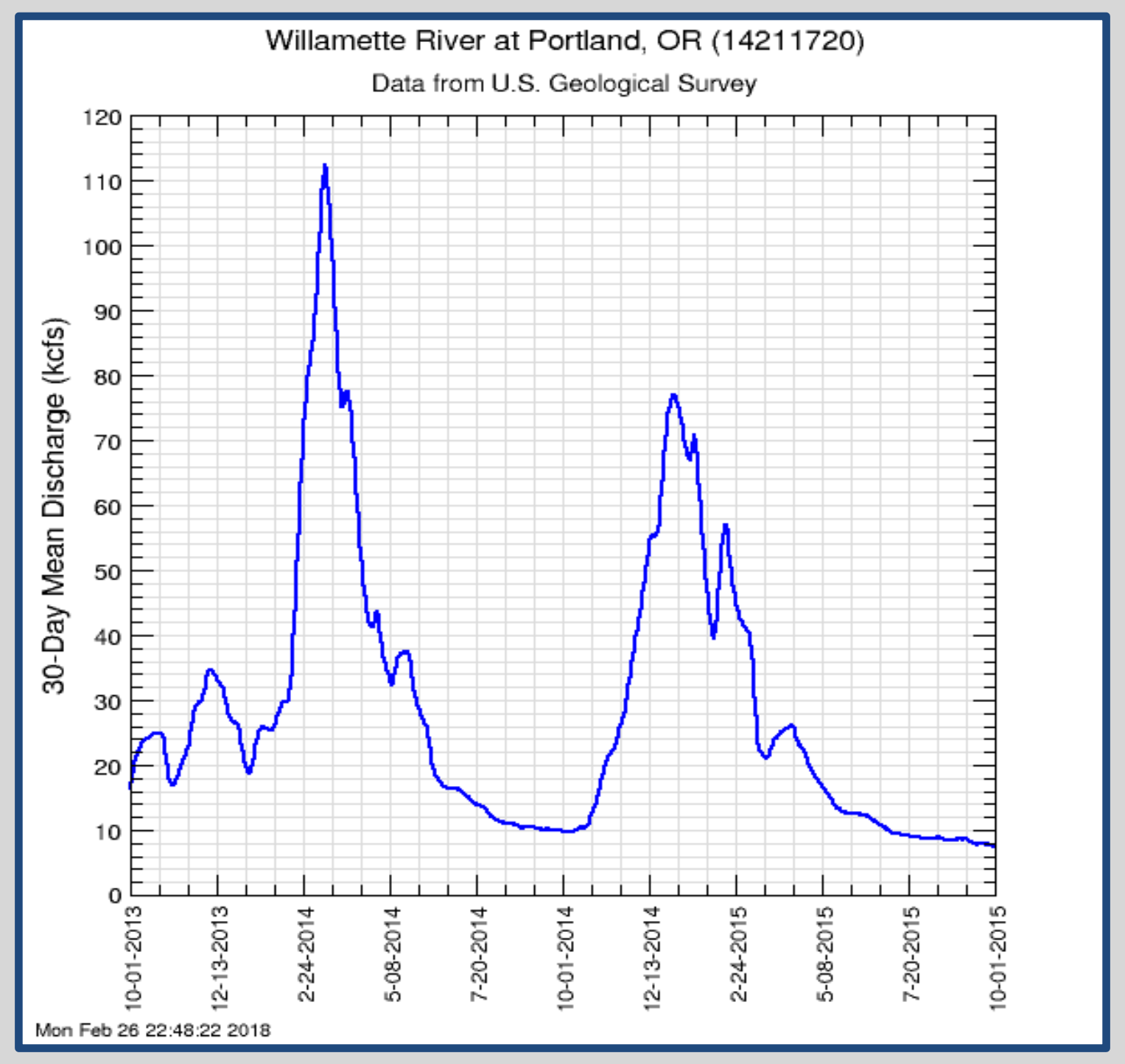
Historic Changes in Snowpack of the Oregon Cascades: Where is all the Snow Going?

Connor Pomeroy, Earth and Physical Sciences Department, Western Oregon University, Monmouth, Oregon, 97361   email: cpomeroy13@mail.wou.edu



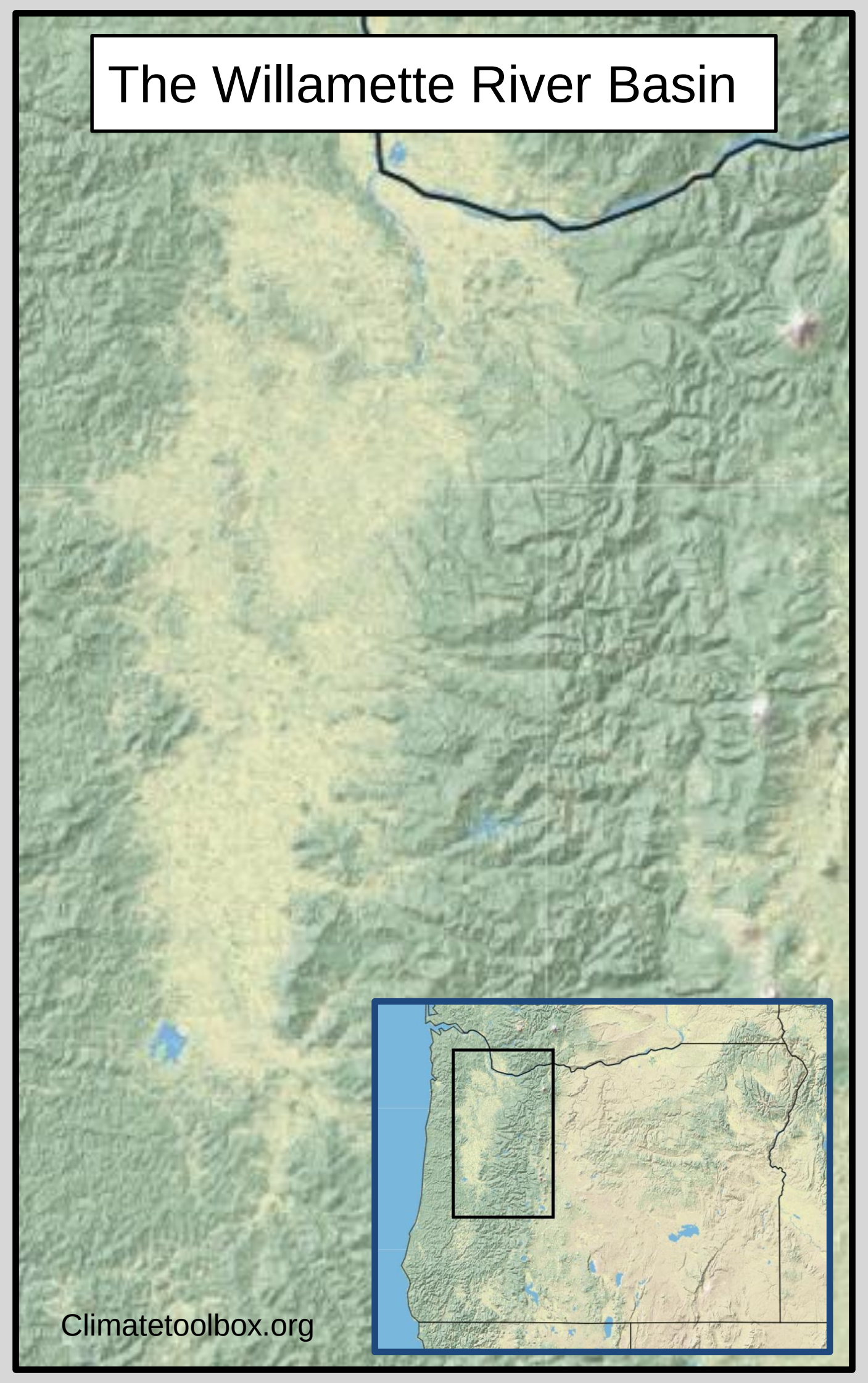
Introduction

- Two of the last ten years have had extraordinarily low snowpacks.
- Water-Year 2014 and 2015 both recorded less than 50% of the historic median value for snow storage (Mote, 2016)
- Rising temperatures have resulted in an increase of rainfall and a decrease in snowfall.

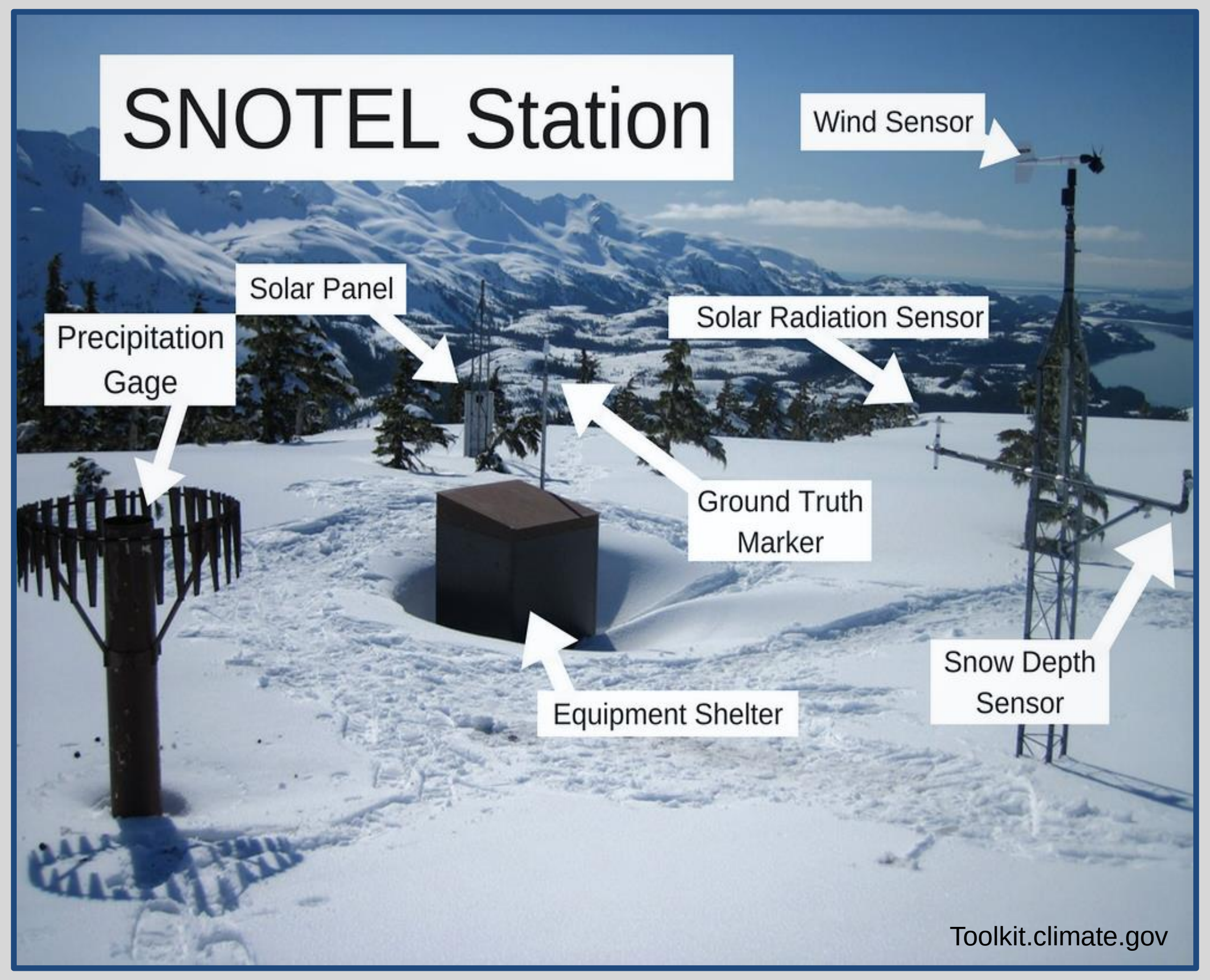


General setting

- The Willamette Water 2100 study looks primarily at the Willamette River basin and includes not only the Willamette River but also the smaller rivers and tributaries that feed into it.
- Rainfall provides most of the water during the winter and spring, with snowpacks supplementing groundwater in the summer and fall which are relatively dry seasons.



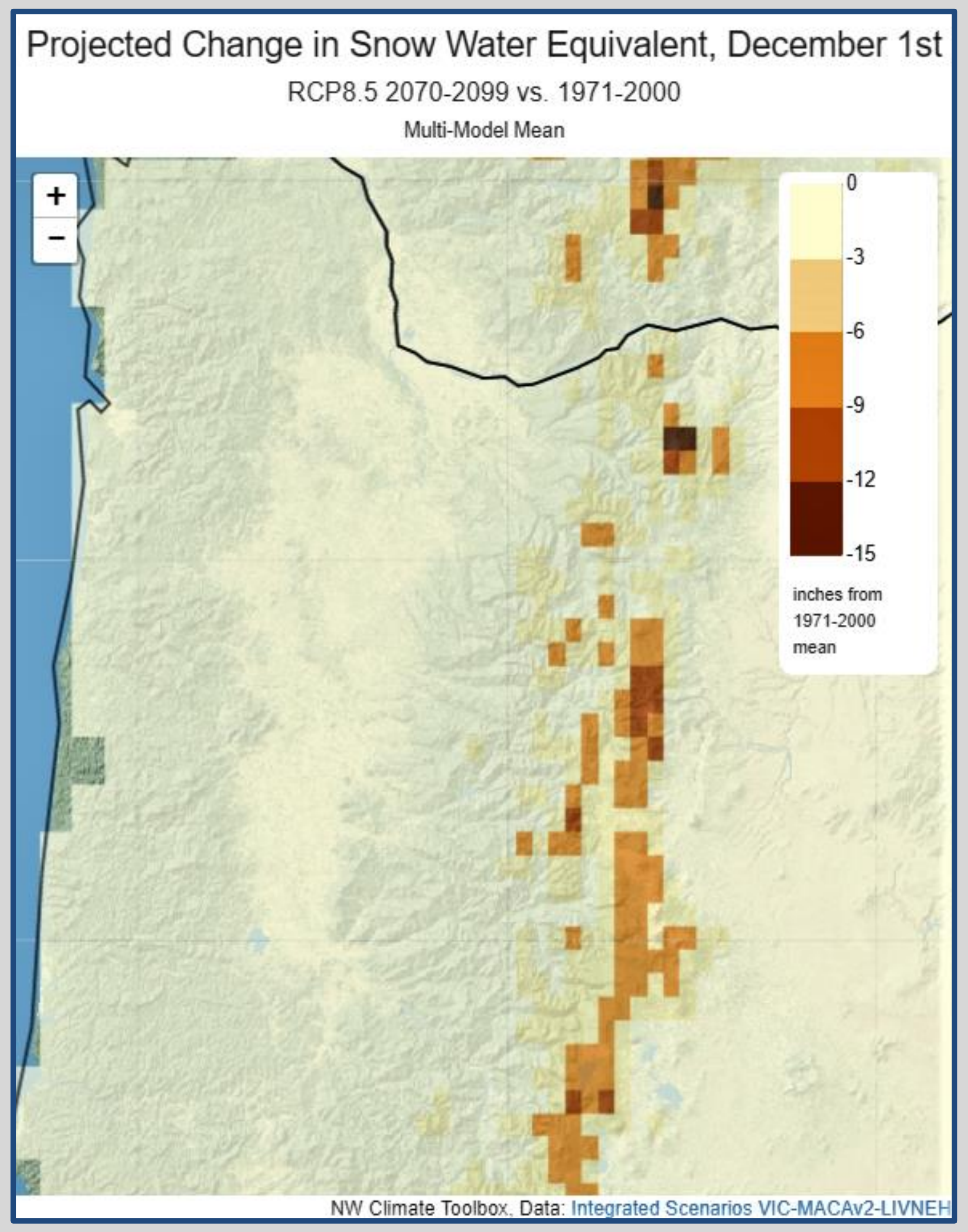
Methodology

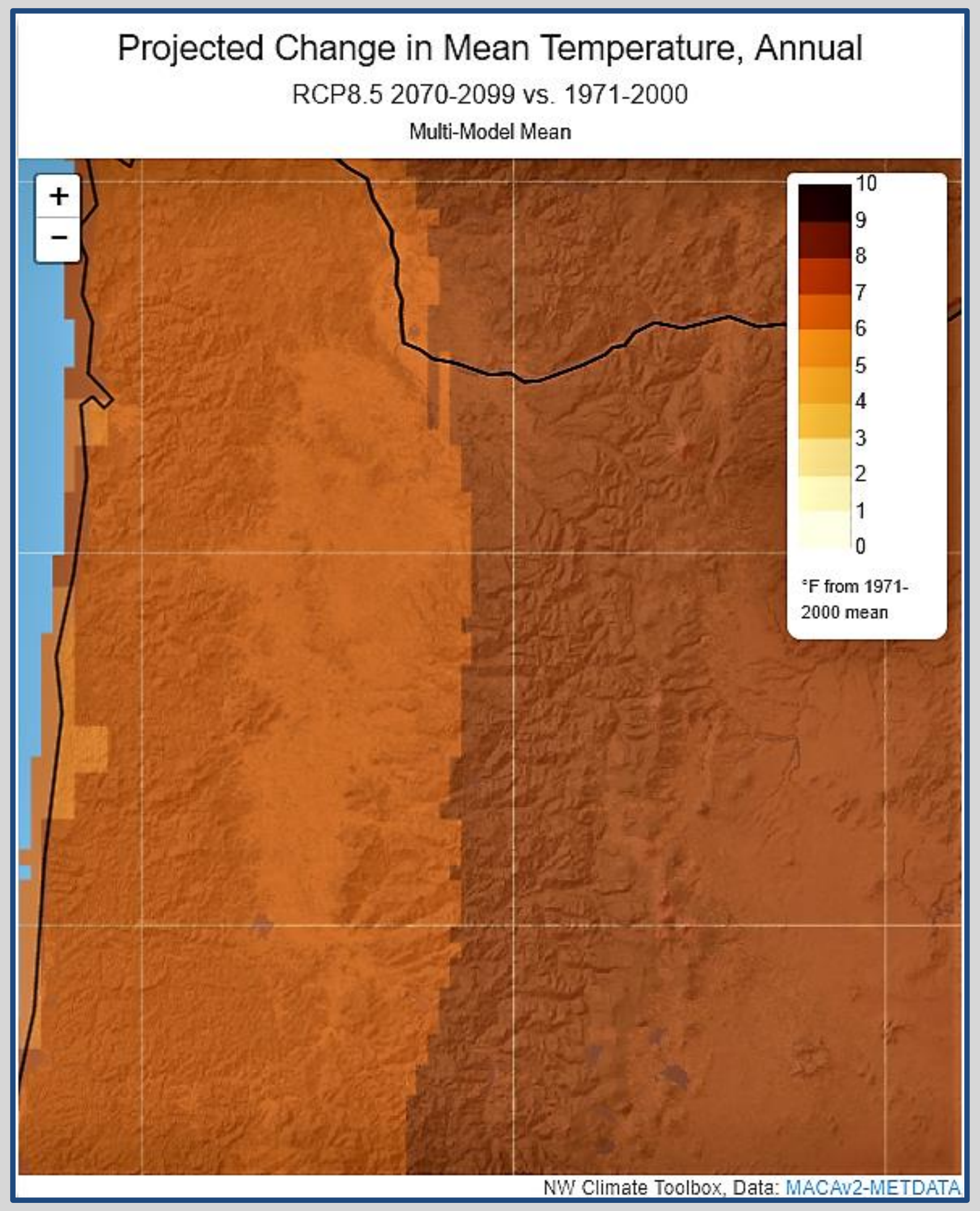


- The Snowpack Telemetry Network (SNOTEL) run by the Natural Resources Conservation Service (NRCS) monitors weather conditions throughout the Pacific Northwest.
- Snow Water Equivalent (SWE) measures the amount of water contained within snowpacks.
- Precipitation and snowfall amounts are gathered every year and compared to the running average of the local environment.
- Future climates are estimated by comparing over 47 Coupled Model Intercomparison Project (CMIP) phase 3 and 5 climate models that take into account local and regional data-sets

Results

- The average Snow Water Equivalent relative to cumulative precipitation (SWE:P) dropped to 0.20 (20% snow, 80% rain) in WY-2014 at an elevation of 1500m while the historic average SWE:P at 1500m is 0.58. In WY-2015 the 0.20 SWE:P was not met until reaching 1750m.
- At the elevation in which snowpacks normally form, WY-2014 recorded a temperature 2.7*C warmer than the historic average, and WY-2015 reached 3.3*C warmer than average for the same elevation.
- Rainfall in WY-2014 was 102% the historical average, and WY-2015 was 81% the historic average.
- By the end of the century the temperature is projected to increase between 2-5*C (4-9*F)





Discussion

- Even though there is a measurable decrease in snowpacks, this is not caused by sizable decrease in precipitation, but by an increase in atmospheric temperatures; this causes the snow zone to retreat higher up the slopes and rain in its place.
- When comparing WY-2014 and WY-2015 against historical data, warm weather shrinking the snowpacks in favor of rain leads to higher chances of flooding in the wet season, and a lower water-table in the dry season.
- If the dry season does not have adequate snowpacks to supply the rivers and tributaries, groundwater depletion is hastened. Even if the region receives the normal amount of precipitation (with an abnormal distribution pattern), the region could be greatly affected by drought.
- Despite data that support warming temperatures and shrinking snowpacks from WY-2014 and WY-2015, scientists will not know the extent of impact on groundwater resources until at the earliest 2022 due to the 7-year mean transit time of groundwater infiltration in the Willamette Basin.

Summary

- The Willamette Valley has been warming since 1901 on average 0.056-0.076*C per decade and shows no signs of slowing down..
- Some areas record temperatures 3.3*C higher than the historic average.
- If we do not change our actions, by the year 2100, the snowpacks will be absent from all but the highest of peaks, temperatures could be 5*C warmer, and groundwater may be all but depleted.

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doi:10.5194/tc-11-331-2017

The Cryosphere

Future snow? A spatial-probabilistic assessment of the extraordinarily low snowpacks of 2014 and 2015 in the Oregon Cascades

Eric A. Sproles[1,2], **Travis R. Roth**[2], **and Anne W. Nolin**[2]

[1]Centro de Estudios Avanzados en Zonas Áridas, Universidad de La Serena, Raul Bitran 1305, La Serena, Chile
[2]College of College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, 104 CEOAS Admin Bldg, Corvallis, OR 97331-5503, USA

Correspondence to: Eric A. Sproles (eric.sproles@gmail.com)

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Abstract. In the Pacific Northwest, USA, the extraordinarily low snowpacks of winters 2013–2014 and 2014–2015 stressed regional water resources and the social-environmental system. We introduce two new approaches to better understand how seasonal snow water storage during these two winters would compare to snow water storage under warmer climate conditions. The first approach calculates a spatial-probabilistic metric representing the likelihood that the snow water storage of 2013–2014 and 2014–2015 would occur under +2 °C perturbed climate conditions. We computed snow water storage (basin-wide and across elevations) and the ratio of snow water equivalent to cumulative precipitation (across elevations) for the McKenzie River basin (3041 km^2), a major tributary to the Willamette River in Oregon, USA. We applied these computations to calculate the occurrence probability for similarly low snow water storage under climate warming. Results suggest that, relative to +2 °C conditions, basin-wide snow water storage during winter 2013–2014 would be above average, while that of winter 2014–2015 would be far below average. Snow water storage on 1 April corresponds to a 42 % (2013–2014) and 92 % (2014–2015) probability of being met or exceeded in any given year. The second approach introduces the concept of snow analogs to improve the anticipatory capacity of climate change impacts on snow-derived water resources. The use of a spatial-probabilistic approach and snow analogs provide new methods of assessing basin-wide snow water storage in a non-stationary climate and are readily applicable in other snow-dominated watersheds.

1 Introduction

In the Pacific Northwest (PNW), USA, mountain snowpacks during the winters of 2013–2014 and 2014–2015 were at or near record lows and well below 50 % of the historic median value (Mote et al., 2016; National Resource Conservation Service, 2014, 2015b). For several decades the Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) network has provided measurements of snow water equivalent (SWE; the amount of water contained within the snowpack) and meteorological data. These station-based measurements have historically served as a proxy for basin-wide snow storage and provide an effective SWE index for estimating streamflow; however under a shifting climate these statistical relationships have also changed (Montoya et al., 2014). The PNW's extremely low snowpacks and subsequent snow water storage of 2013–2014 and 2014–2015 highlight the limitations of location-specific measurements in a shifting climate.

On 1 March 2015, 47 % of snow monitoring sites in the Willamette River basin (WRB, 29 730 km^2, Fig. 1) registered zero SWE, while snow was still present at higher elevations. The absence of snow during the winter of 2014–2015 stands in contrast to cumulative winter precipitation, which was at 83 % of normal (778 mm) for November–February (derived from PRISM (Parameter-elevation Relationships on Independent Slopes Model) data (Daly et al., 2008). While the concurrent drought in California received substantial attention, the economic and environmental impacts in the PNW were also profound. These two extremely low snowpacks

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WESTERN OREGON UNIVERSITY
Geology & Earth Science

Projecting future climate of the Pacific Northwest

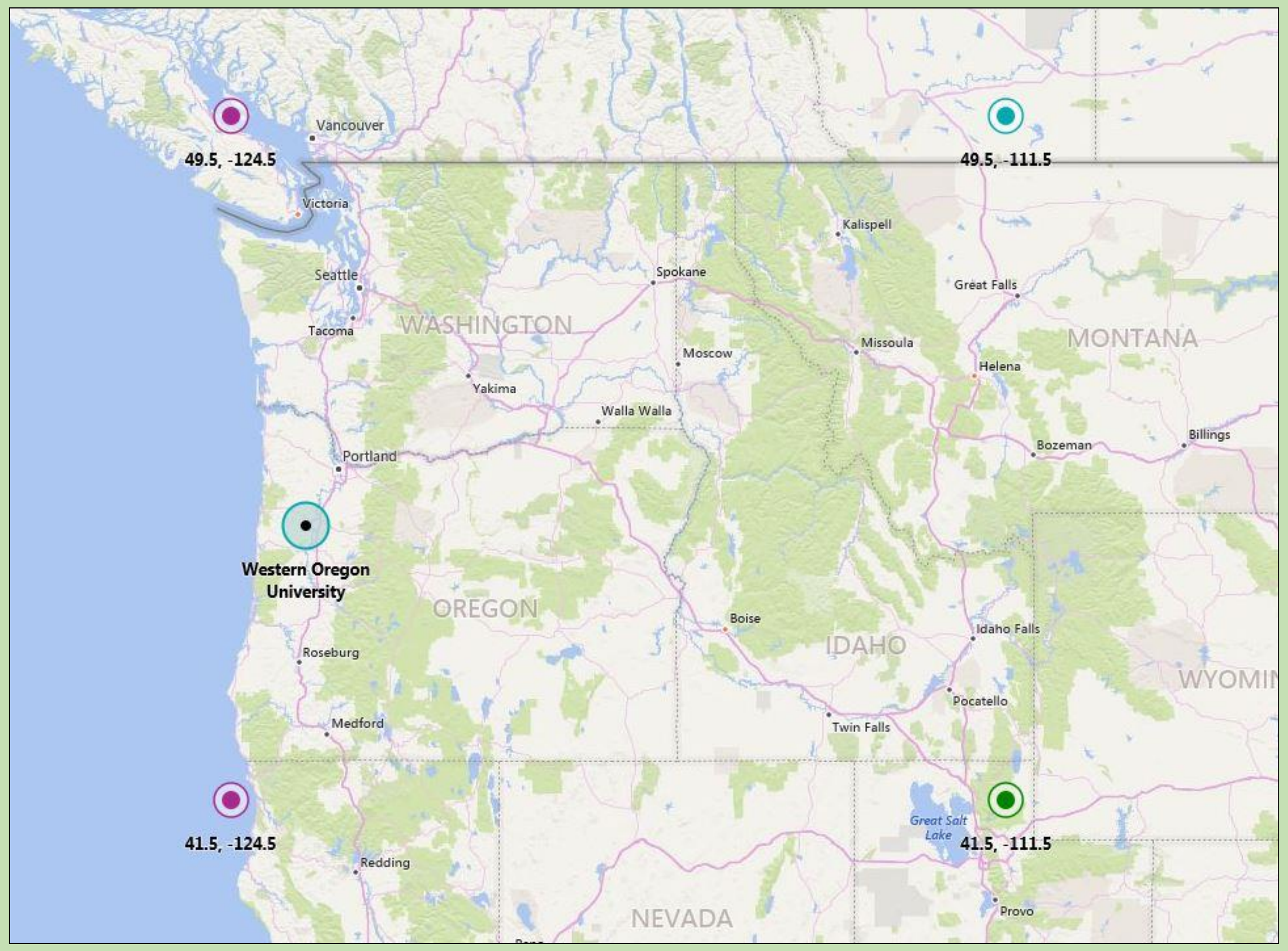
Kyler Freilinger, Western Oregon University
email: kyler.freilinger@gmail.com

Introduction

The topic at hand is making future climate predictions. The predictions will be made using Global Climate Models (GCMs). The GMCs will be evaluated using detailed measurements. They will be used to predict the climatic condition of the Pacific Northwest (PNW) in the 21st century, using data from the 20th century.

Location and Study Area

The PNW is defined as 41.5°N to 49.5°N and 124.5°W to 111.5°W. This is approximately 322870 square miles. Cells are used to quantize the data. On average, cell sizes are 0.5°x0.5°. The area of the PNW is 416 cells. This is approximately 776 square miles per cell. One side of a cell is just over from WOU to OSU.

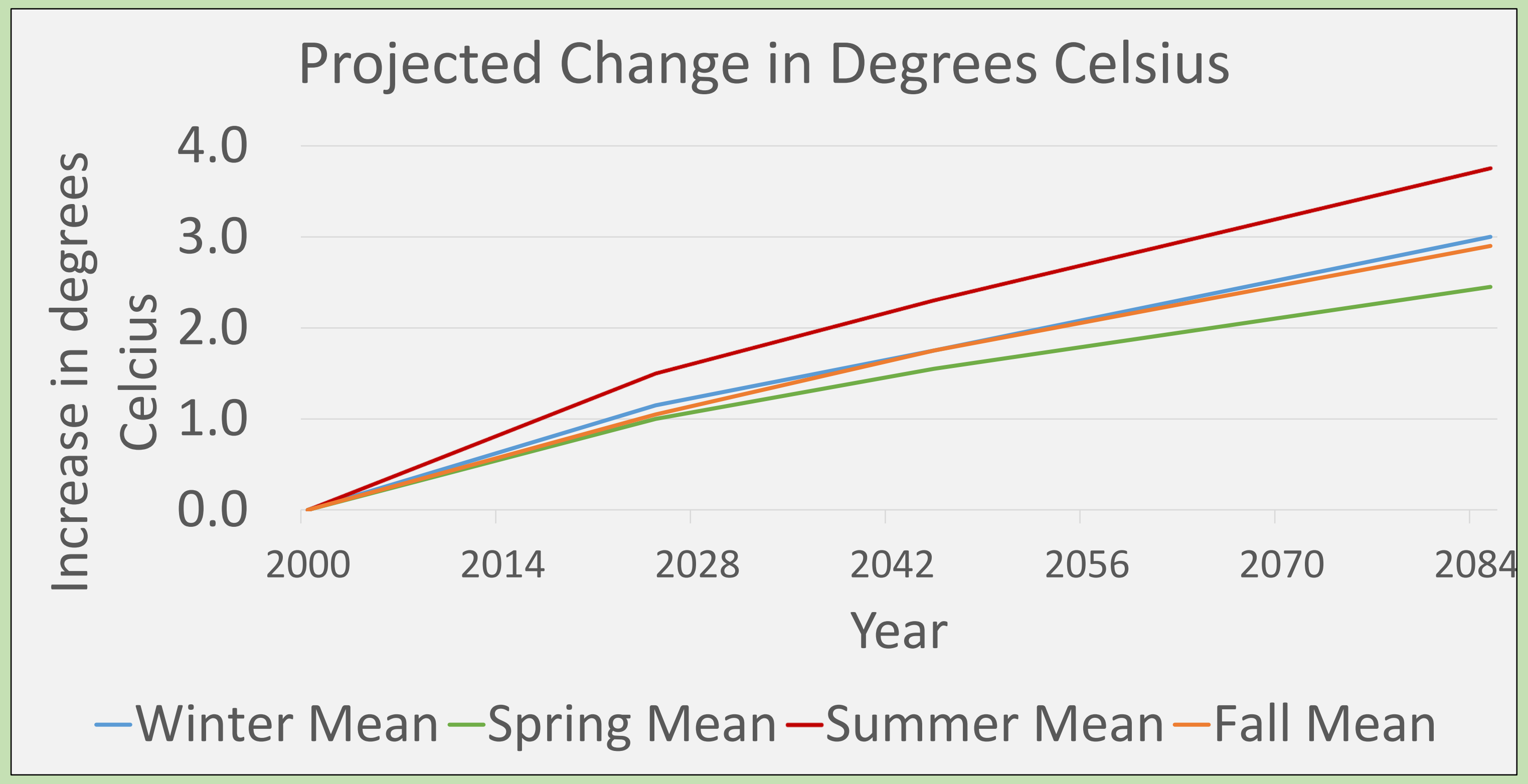


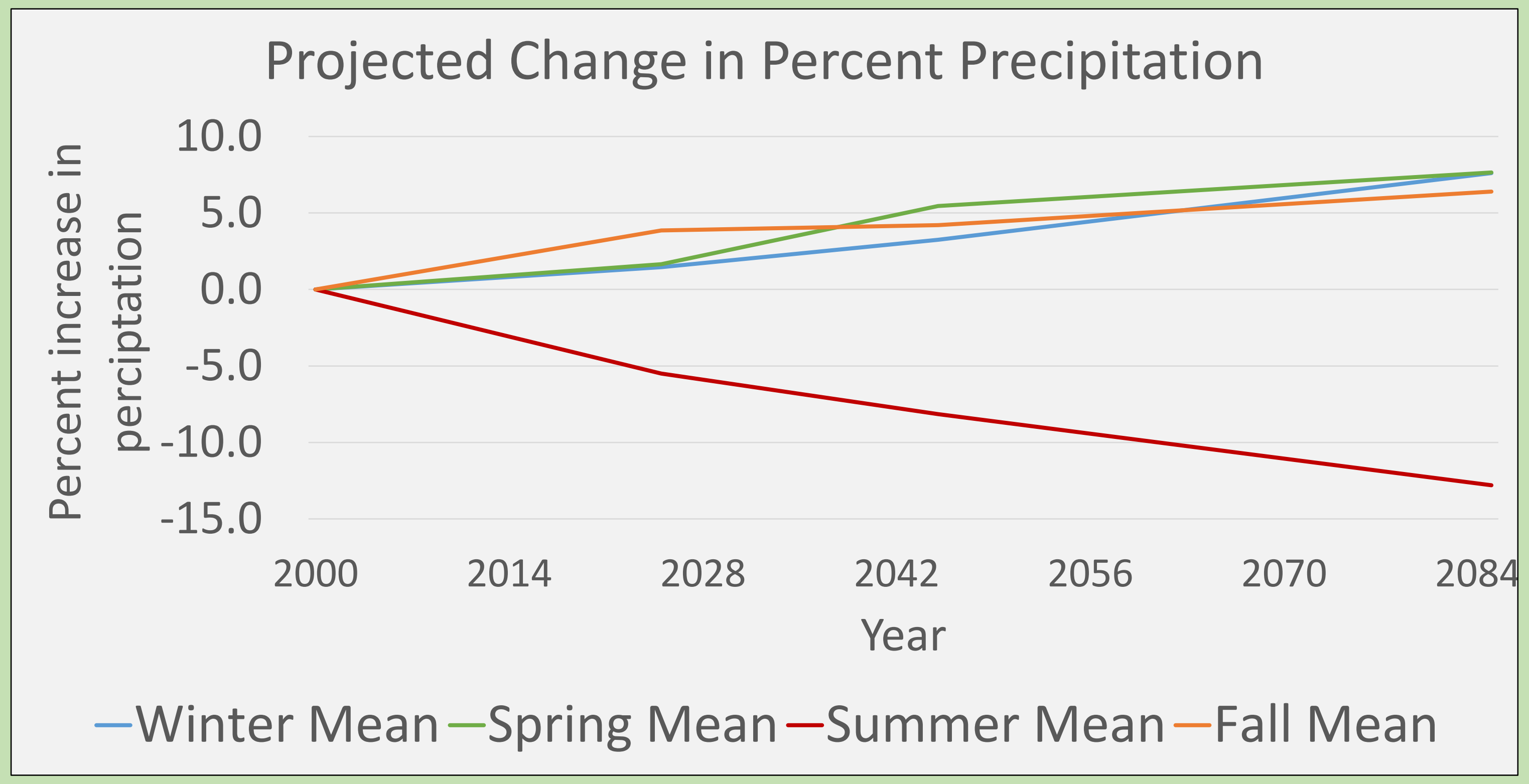
Evaluating Global Climate Models

To evaluate models, the models are used to try and recreate a past climate. For our purposes this is the climate of the PNW in the 20th century. Some of the metrics used include annual mean, seasonal mean, standard deviation, and overall trends.

Data Acquisition

Data was used from four periods 2000s, 2020s, 2040s, and 2080s. The data from these periods were then compared to the conditions of the 20th century. The year 2000 is used as a base line.





Results

Annual temperature and precipitation changes
- Precipitation and temperature will increase
- The rate of increase will decline over time

Seasonal temperature and precipitation changes
- Temperature will increase in all seasons
- Precipitation will increase in Winter, Spring, and Fall. However, precipitation will decrease in Summer.

Summary

The climate of the Pacific Northwest is changing, temperatures and precipitation are both increasing. However, temperatures and precipitation, while increasing, are increasing at a slower rate. The only exception being that summers at the same rate will be getting dryer.

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Rupp DE, Abatzoglou JT, Hegewisch KC, Mote PW. 2013. **Evaluation CMIP5 20th century climate simulations for the Pacific Northwest USA**. Journal of Geophysical Research: Atmospheres. 118:10,884-10,906

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JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 10,884–10,906, doi:10.1002/jgrd.50843, 2013

Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA

David E. Rupp,[1] John T. Abatzoglou,[2] Katherine C. Hegewisch,[2] and Philip W. Mote[1]

Received 24 April 2013; revised 8 August 2013; accepted 13 September 2013; published 10 October 2013.

[1] Monthly temperature and precipitation data from 41 global climate models (GCMs) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) were compared to observations for the 20th century, with a focus on the United States Pacific Northwest (PNW) and surrounding region. A suite of statistics, or metrics, was calculated, that included correlation and variance of mean seasonal spatial patterns, amplitude of seasonal cycle, diurnal temperature range, annual- to decadal-scale variance, long-term persistence, and regional teleconnections to El Niño Southern Oscillation (ENSO). Performance, or credibility, was assessed based on the GCMs' abilities to reproduce the observed metrics. GCMs were ranked in their credibility using two methods. The first simply treated all metrics equally. The second method considered two properties of the metrics: (1) redundancy of information (dependence) among metrics, and (2) confidence in the reliability of an individual metric for accurately ranking models. Confidence was related to how robust the estimate of the metric was to ensemble size, given that for most of the models only a small number of ensemble members (i.e., realizations of the 20th century) were available. A cursory comparison with 24 CMIP3 models revealed few differences between the two generations of models with respect to the statistics analyzed.

Citation: Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote (2013), Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA, *J. Geophys. Res. Atmos.*, *118*, 10,884–10,906, doi:10.1002/jgrd.50843.

1. Introduction

[2] Over the last several years, climate change impacts assessments at regional and local scales have used 21st century climate projections from global climate models (GCMs) participating in the World Climate Research Programme's Coupled Model Intercomparison Project Phase 3 (CMIP3). With Phase 5 (CMIP5) now well underway, and most simulations from the new generation of GCMs already available, many impact assessments and other applications are beginning to use projections from CMIP5. The question, then, of how well the CMIP5 GCMs simulate climate at regional scales is of great interest to both researchers and resource managers.

[3] Two primary goals motivate the evaluation of GCMs. The first is the principal goal of model developers' evaluation efforts: to identify model deficiencies and potential processes responsible for the deficiencies. The second, and the one that motivates this paper, is more application driven: to provide information about model uncertainty beyond that associated with climate projections. The latter evaluation is critical as these models provide descriptions of climate change and are used in impacts modeling. There are a variety of schools of thought about the use of model evaluations for applications, ranging from "model democracy" (e.g., *Knutti* [2010]) which posits that each model simulation presents an equally valid and equally likely depiction of the future, to evaluation that is provided for informational purposes but not used to modify projections of the future (e.g., *Mote and Salathé* [2010]), to model weighting or culling, in which a model's performance at simulating 20th century climate (its "reliability" or "credibility") is taken into account numerically in future projections (e.g., *Giorgi and Mearns* [2002]). Model culling is effectively weighting with binary weights. The justification for weighting or culling models—necessarily an untestable hypothesis—is that a model that fails to reproduce aspects of the past climate will be less likely to produce a correct projection of future climate. *Mote and Salathé* [2010] found that weighting models made little difference in projected seasonal means of temperature and precipitation in the Northwest, though for other regions the same, or similar, approach made a bigger difference [*Giorgi and Mearns*, 2002; *Brekke et al.*, 2008; *Pitman and Perkins*, 2008]. Others have demonstrated that the appropriate determination of model weights is not trivial and that weighting may simply serve to increase uncertainty [*Christensen et al.*, 2010; *Weigel et al.*, 2010]. In addition to quantifying the mean projected changes, though, it is often of interest to quantify the uncertainty, and for these purposes the model evaluation may have a bigger impact simply by reducing the number of potential outlier models.

Additional supporting information may be found in the online version of this article.

[1] Oregon Climate Change Research Institute, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.

[2] Department of Geography, University of Idaho, Moscow, Idaho, USA.

Corresponding author: D. E. Rupp, Oregon Climate Change Research Institute, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA. (david.rupp@oregonstate.edu)

2169-897X/13/10.1002/jgrd.50843

This article was corrected on 7 MAY 2015. See the end of the full text for details.

WESTERN OREGON UNIVERSITY
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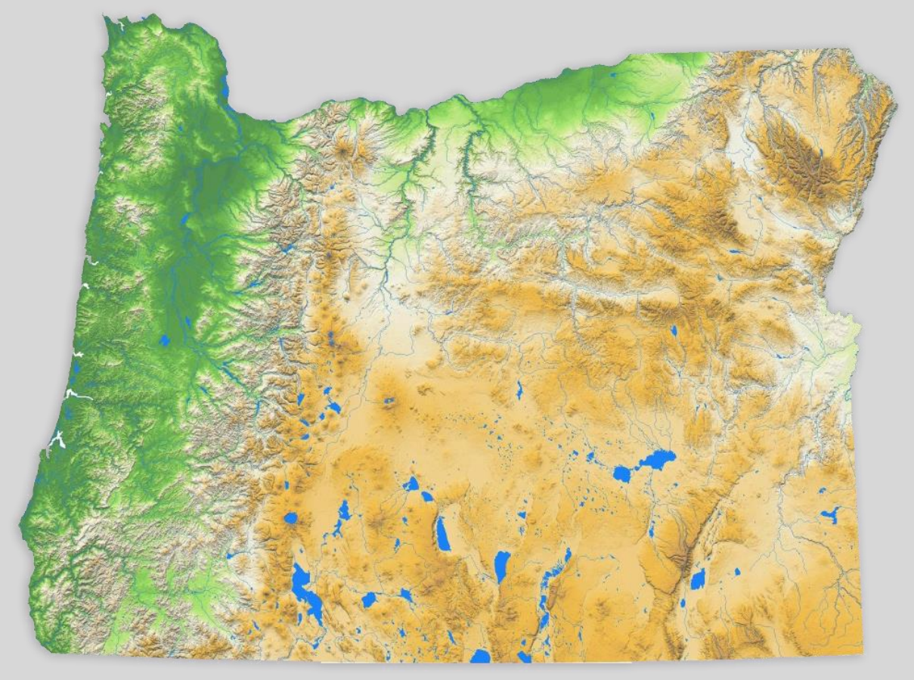
Assessing Water Resource Vulnerability in the Columbia River Basin

Kyle Warren, Earth and Physical Sciences Department, Western Oregon University, Monmouth, Oregon, 97361
email: kwarren13@mail.wou.edu

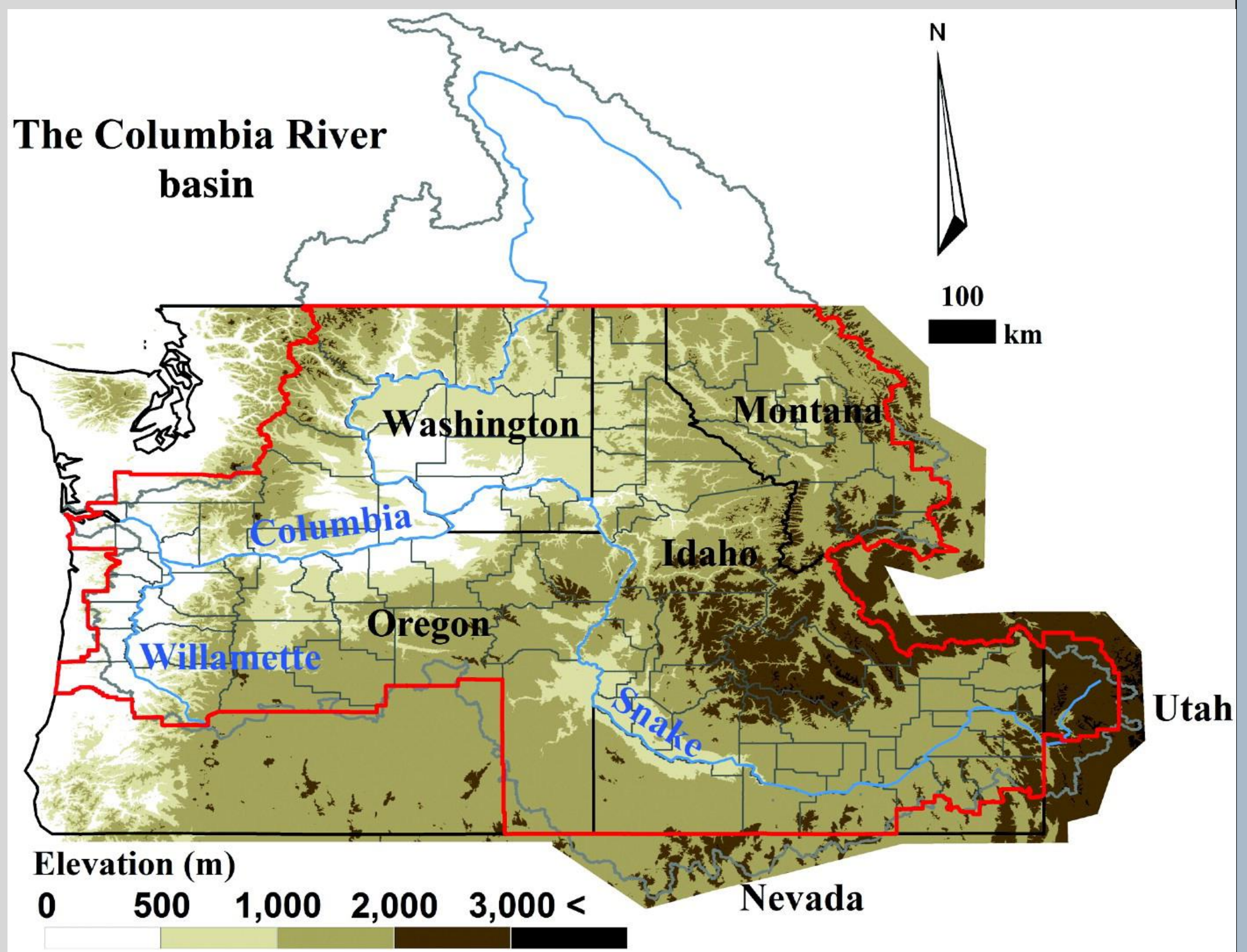


Abstract

The authors investigated water resource vulnerability in the US portion of the Columbia River Basin (CRB) using multiple indicators representing water supply, water demand, and water quality. Based on the US county scale, spatial analysis was conducted using various biophysical and socio-economic indicators that control water vulnerability. Water supply vulnerability and water demand vulnerability exhibited a similar spatial clustering of hotspots in areas where agricultural lands and variability of precipitation were high but dam storage capacity was low. The hotspots of water quality vulnerability were clustered around the main stem of the Columbia River where major population and agricultural centers are located. This multiple equal weight indicator approach confirmed that different drivers were associated with different vulnerability maps in the sub-basins of the CRB. Water quality variables are more important than water supply and water demand variables of the Willamette River Basin (WRB), whereas water supply and demand variables are more important than water quality variables are in the Upper Snake and Upper Columbia River Basins. This result suggests that current water resources management coordination of water management and practices drive much of the water vulnerability within the study area. The analysis suggests the need for increased coordination of water management across multiple levels of water governance to reduce water resource vulnerability in the CRB and a potentially different weighting scheme that explicitly takes into account the input of various water stakeholders.

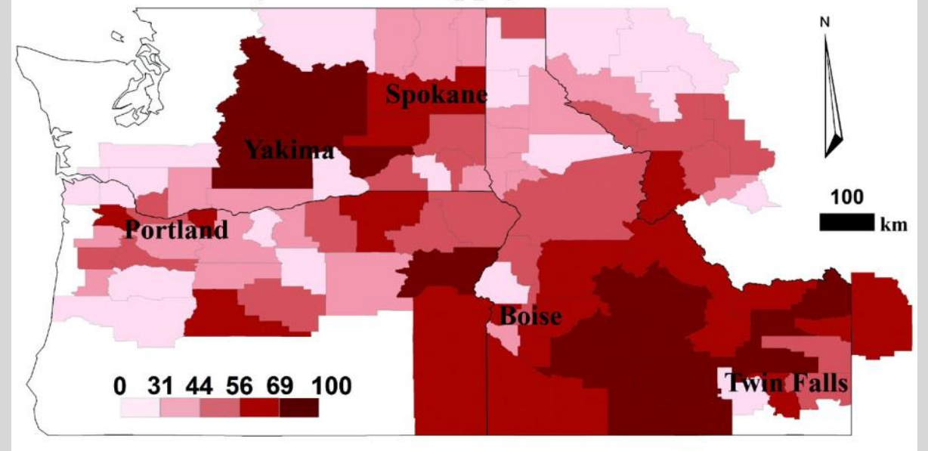
Introduction

The goal of these papers was to understand the Columbia River basin so that we can further predict what will happen in the future. Its important to understand water supply vulnerability, water demand vulnerability, and water quality vulnerability. Focusing in on the Willamette valley, the population is expected to double in the next 50-60 years, so we need to have an understanding of the water issues. The Columbia River Basin is the largest basin in the Pacific Northwest of the United States. In the coming years we are going to have to deal with both population increase and climate change. These papers primarily focused on the human side of this issue, so that will be the primary focus here.

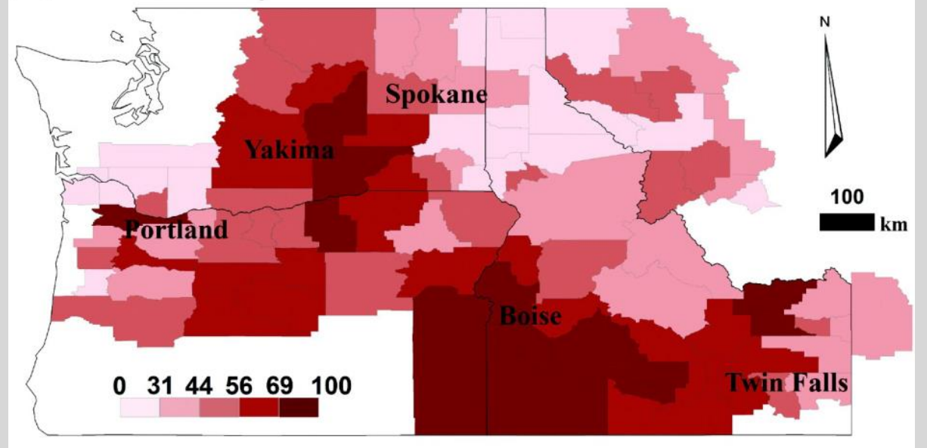


Water Vulnerability

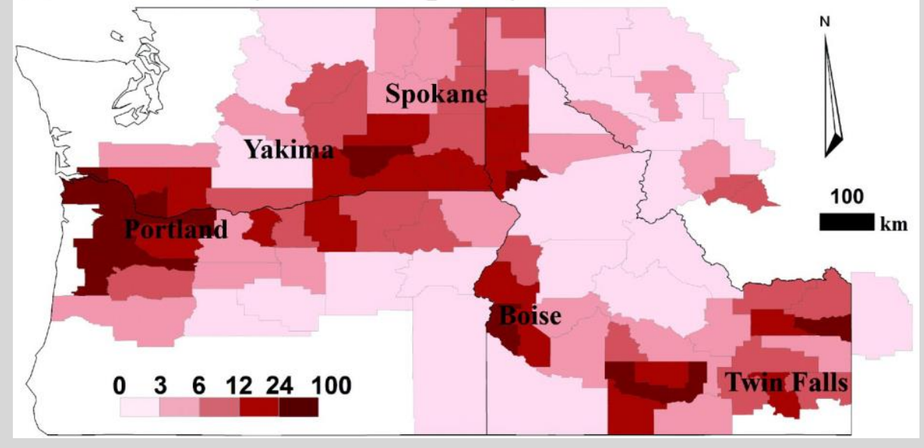
(a) Vulnerability of water supply



(b) Vulnerability of water demand



(c) Vulnerability of water quality



Vulnerability Overview

- Defined as a measure of the magnitude of a system's potential for failure.
- Can include shocks, stresses, and or disturbances.

Water Supply Vulnerability

- A combination of both precipitation and water resource availability.
- Terrain can play a part in water supply.
- Dams are a way to help control water supply.

Water Demand Vulnerability

- Mostly related to socio-economic infrastructure.
- Lots of demand due to lots of agriculture.
- Will become a big issue as the population grows.

Water Quality Vulnerability

- Dependent on temperature, nitrogen and phosphorus levels, erosion potential, and algal blooms.
- Agriculture pesticide, herbicide and fertilizer contamination.

The Results

Water Supply

•Seasonal runoff contributes more in the Willamette Valley counties.
•Major Cities like Portland have a high number of days with heavy precipitation and low number of days with no precipitation.
•Snow pack plays a part in supply in the summer/spring months.
•Supply Vulnerability is dependent on the area. The WRB is fighting different issues than the Yakima and Spokane areas.

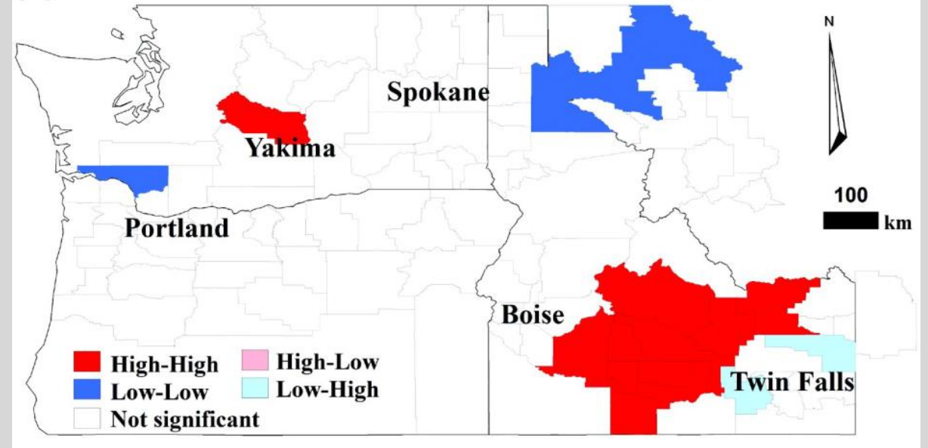
Water Demand

•In the Willamette Valley its expected to increase by 43% in the next 20 years
•Water demand maps look very similar to irrigation maps.
•Major uses include agriculture, then human use in the population centers.

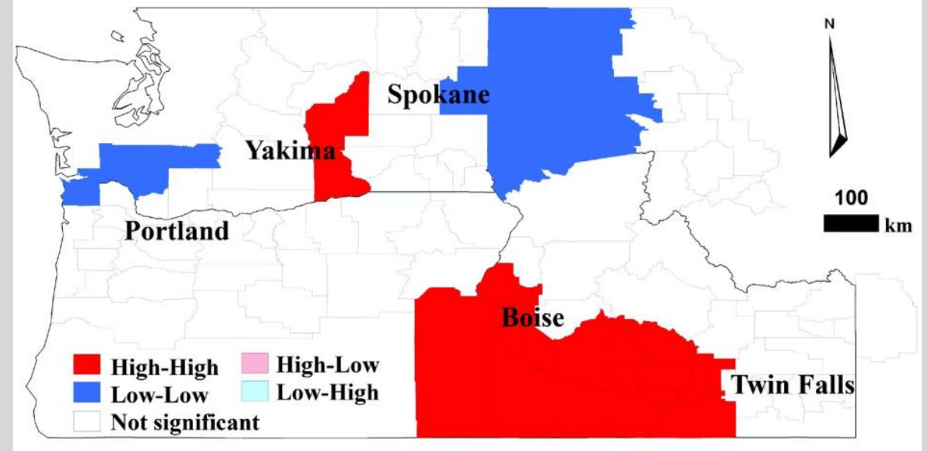
Water Quality

•Quality is the worst close to larger cities due to contamination
•Rural counties account for 60% of the CRB have moderately low vulnerability for water quality.

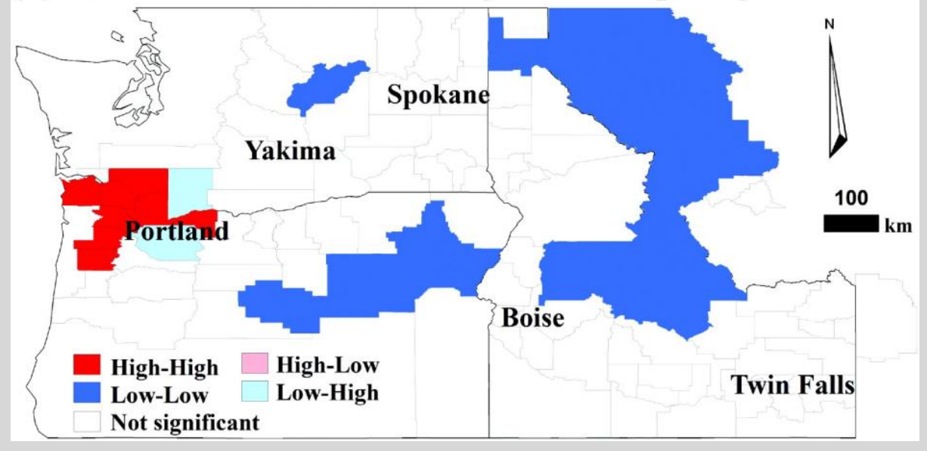
(a) LISA cluster - Vulnerability of water supply



(b) LISA cluster - Vulnerability of water demand



(c) LISA cluster - Vulnerability of water quality



The Willamette Valley

- A majority of the Willamette Valley is agriculture use.
- Water Quality is a worry due to the amount of fertilizer and possible groundwater contamination.
- As the population increases there will be more of a need for food.
- Water Quality effects people that live in the area along with local fish and other animals.
- As the population increases the demand for water will increase making water more scarce.
- Water storage could be an issue for the upcoming population boom

- There has been a channel simplification of the Willamette River over the last 200 years.
- There is only about 20% of the vegetation of what used to be along the river.
- Much water has been diverted for agricultural use. Thanks to this many second, third and fourth order streams dry up in the summer months.

What Can We Do?

When looking at the Columbia River Basin there is a huge variety of climates and different things going on. But when broken down by county neighboring counties look pretty similar to each other. Water management will become very important in the coming future if it isn't already. We will need to encourage our local and state governments to work together to create policies so that everyone can benefit later down the road. Water supply, demand, and quality are all extremely important. Land-use is one of the most important factors when it comes to water. If we can smart and work efficiently with our land we should be able to make everything work smoothly. The Columbia River Basin is huge, but if we work together on more of a regional scale.

Conclusion

Water quality vulnerability, water demand vulnerability, and water quality vulnerability are all important to us. The information from these papers did a good job of putting together a lot of studies done, and creating a great starting point for what we can do to prepare for the future. The most important thing we should be doing is working on a regional level. If we can prioritize land use and be smart about how we use the limited land that we have for both agricultural and human use then we should make out alright. We cannot control climate change on a local level, but we can focus on how we work with the water that we have. Given the data and information we have We should be able to solve the issue of water in the Columbia Basin.

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Heejun Chang , Il-Won Jung , Angela Strecker , Daniel Wise , Martin Lafrenz, Vivek Shandas , Hamid Moradkhani , Alan Yeakley , Yangdong Pan , Robert Bean , Gunnar Johnson & Mike Psaris (2013). Water Supply, Demand, and Quality Indicators for Assessing the Spatial Distribution of Water Resource Vulnerability in the Columbia River Basin, Atmosphere-Ocean, 51:4, 339-356, DOI: 10.1080/07055900.2013.777896

Joan P. Baker, David W. Hulse, Stanley V. Gregory, Denis White, John Van Sickle, Patricia A. Berger, David Dole, and Nathan H. Schumaker (2004). Ecological Society of America. Vol 14 No. 2 Alternative Futures for the Willamette River Basin, Oregon. p. 313-324

Water Supply, Demand, and Quality Indicators for Assessing the Spatial Distribution of Water Resource Vulnerability in the Columbia River Basin

Heejun Chang[1,*], Il-Won Jung[1], Angela Strecker[2], Daniel Wise[3], Martin Lafrenz[1], Vivek Shandas[4], Hamid Moradkhani[5], Alan Yeakley[2], Yangdong Pan[2], Robert Bean[1], Gunnar Johnson[2] and Mike Psaris[1]

[1]*Department of Geography, Portland State University, Portland, Oregon, USA*
[2]*Department of Environmental Sciences and Management, Portland State University, Portland, Oregon, USA*
[3]*US Geological Survey, Oregon Water Science Center, Portland, Oregon, USA*
[4]*School of Urban Studies and Planning, Portland State University, Portland, Oregon, USA*
[5]*Department of Civil and Environmental Engineering, Portland State University, Portland, Oregon, USA*

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ABSTRACT *We investigated water resource vulnerability in the US portion of the Columbia River basin (CRB) using multiple indicators representing water supply, water demand, and water quality. Based on the US county scale, spatial analysis was conducted using various biophysical and socio-economic indicators that control water vulnerability. Water supply vulnerability and water demand vulnerability exhibited a similar spatial clustering of hotspots in areas where agricultural lands and variability of precipitation were high but dam storage capacity was low. The hotspots of water quality vulnerability were clustered around the main stem of the Columbia River where major population and agricultural centres are located. This multiple equal weight indicator approach confirmed that different drivers were associated with different vulnerability maps in the sub-basins of the CRB. Water quality variables are more important than water supply and water demand variables in the Willamette River basin, whereas water supply and demand variables are more important than water quality variables in the Upper Snake and Upper Columbia River basins. This result suggests that current water resources management and practices drive much of the vulnerability within the study area. The analysis suggests the need for increased coordination of water management across multiple levels of water governance to reduce water resource vulnerability in the CRB and a potentially different weighting scheme that explicitly takes into account the input of various water stakeholders.*

RÉSUMÉ *[Traduit par la rédaction] Nous étudions la vulnérabilité de la ressource en eau dans la partie étatsunienne du bassin du fleuve Columbia à l'aide d'indicateurs multiples représentant l'apport d'eau, la demande en eau et la qualité de l'eau. En nous basant sur l'échelle des comtés des États–Unis, nous avons fait une analyse spatiale à l'aide de divers indicateurs biophysiques et socio-économiques qui déterminent la vulnérabilité de l'eau. La vulnérabilité de l'apport d'eau et la vulnérabilité de la demande en eau ont exhibé un regroupement spatial similaire de points chauds dans les régions où il y avait beaucoup de terres agricoles et une grande variabilité dans les précipitations mais où il y avait une faible capacité de stockage par des barrages. Les points chauds de vulnérabilité de la qualité de l'eau étaient regroupés autour du bras principal du fleuve Columbia, où sont situés les principaux centres urbains et agricoles. Cette approche basée sur des indicateurs multiples de poids égaux a confirmé que différents facteurs étaient associés à différentes cartes de vulnérabilité dans les sous-bassins du bassin du fleuve Columbia. Les variables de qualité de l'eau sont plus importantes que les variables d'apport d'eau et de demande en eau dans le bassin de la rivière Willamette alors que les variables d'apport d'eau et de demande en eau sont plus importantes que les variables de qualité de l'eau dans les bassins des parties supérieures de la rivière Snake et du fleuve Columbia. Ce résultat donne à penser que la gestion et les pratiques courantes en matière de ressources en eau déterminent en grande partie la vulnérabilité à l'intérieur de la région étudiée. L'analyse semble indiquer le besoin d'une plus grande coordination de la gestion de l'eau entre plusieurs ordres de gouvernance de l'eau pour réduire la vulnérabilité de la ressource dans le bassin du fleuve Columbia et d'un schéma utilisant des poids différents qui prendrait explicitement en compte les commentaires de différents intéressés en matière d'eau.*

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[*] Corresponding author's email: changh@pdx.edu

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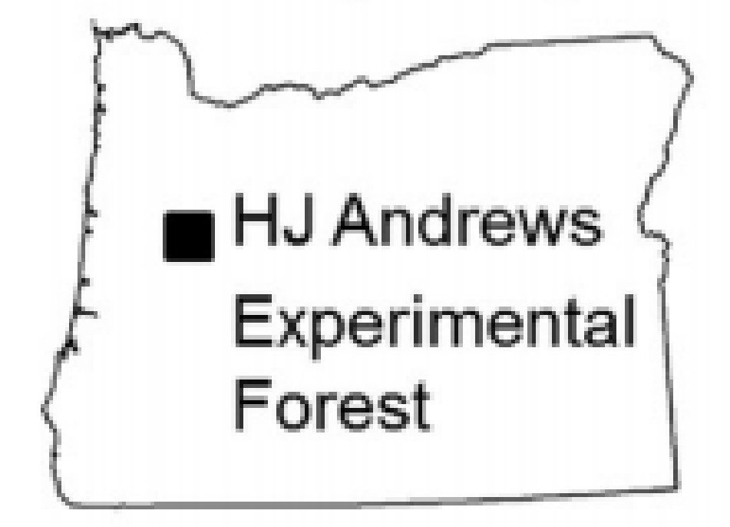
Canadian Meteorological and Oceanographic Society

WESTERN OREGON UNIVERSITY
Geology & Earth Science

Temporal Dynamics of Catchment Transit Times from Stable Isotope Data

Julian Klaus, Kwok P. Chun, Kevin J. McGuire, and Jeffrey J. McDonnell, 2015

Summary Review by David Solvedt, B.S. Environmental Chemistry, Western Oregon University, Monmouth, OR 97361, dsolvedt13@wou.edu

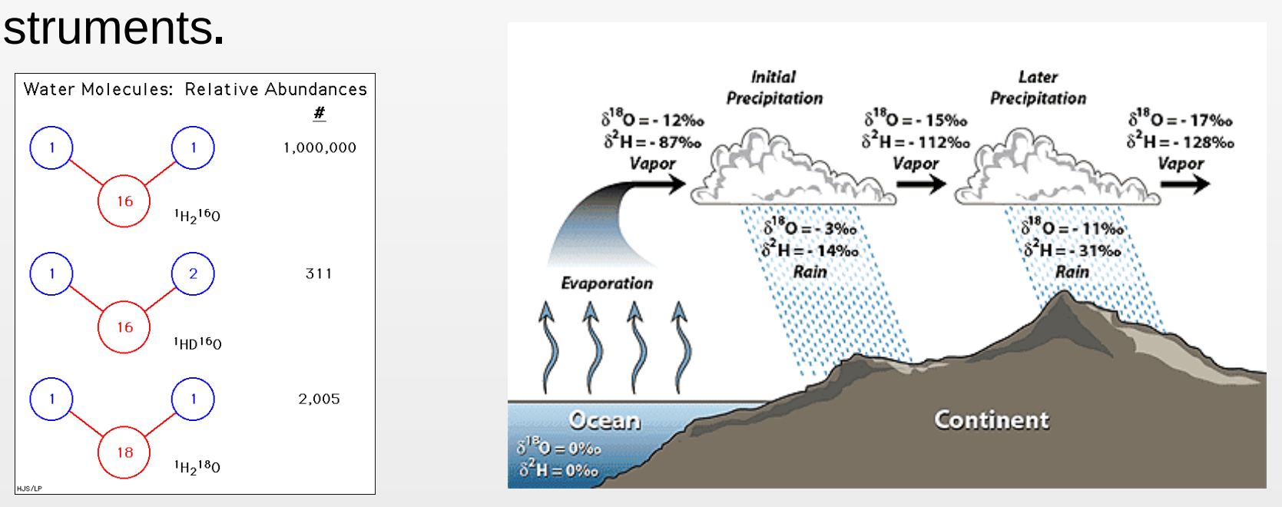


1 Background

Stable isotope tracers are an effective tool utilized by hydrologists to understand the functions and properties of watersheds. Among others, these tracers can provide valuable information regarding the source of precipitation, flow path distribution of water through a catchment, and the relative age of water discharged.

Catchments are hydrological systems where there are inputs and outputs of water, sediments, and nutrients that are cycled through diverse pathways across the surface and through the subsurface within a topographically restricted region.

Isotopes are atoms (such as oxygen or hydrogen) which possess an identical number of protons, but differing number of neutrons. For example, oxygen has 8 protons and 8 electrons, but can possess either 8, 9, or 10 neutrons (three isotopes of oxygen). These can account for oxygen having isotopic molecular masses (the number of protons + neutrons) of either 16 (light), 17, or 18 (heavy). Likewise, hydrogen may have either 1 or 2 neutrons in its stable isotopes. A water molecule (a combination of 1oxygen and 2 hydrogen atoms) may therefore exist as a combination of varying isotopes of oxygen and hydrogen (see Figure 0). These stable isotopes of water (here we focus on just the light H_2O^{16} and heavy H_2O^{18}) have slightly different physical properties, and can be distinguished with analytical instruments.

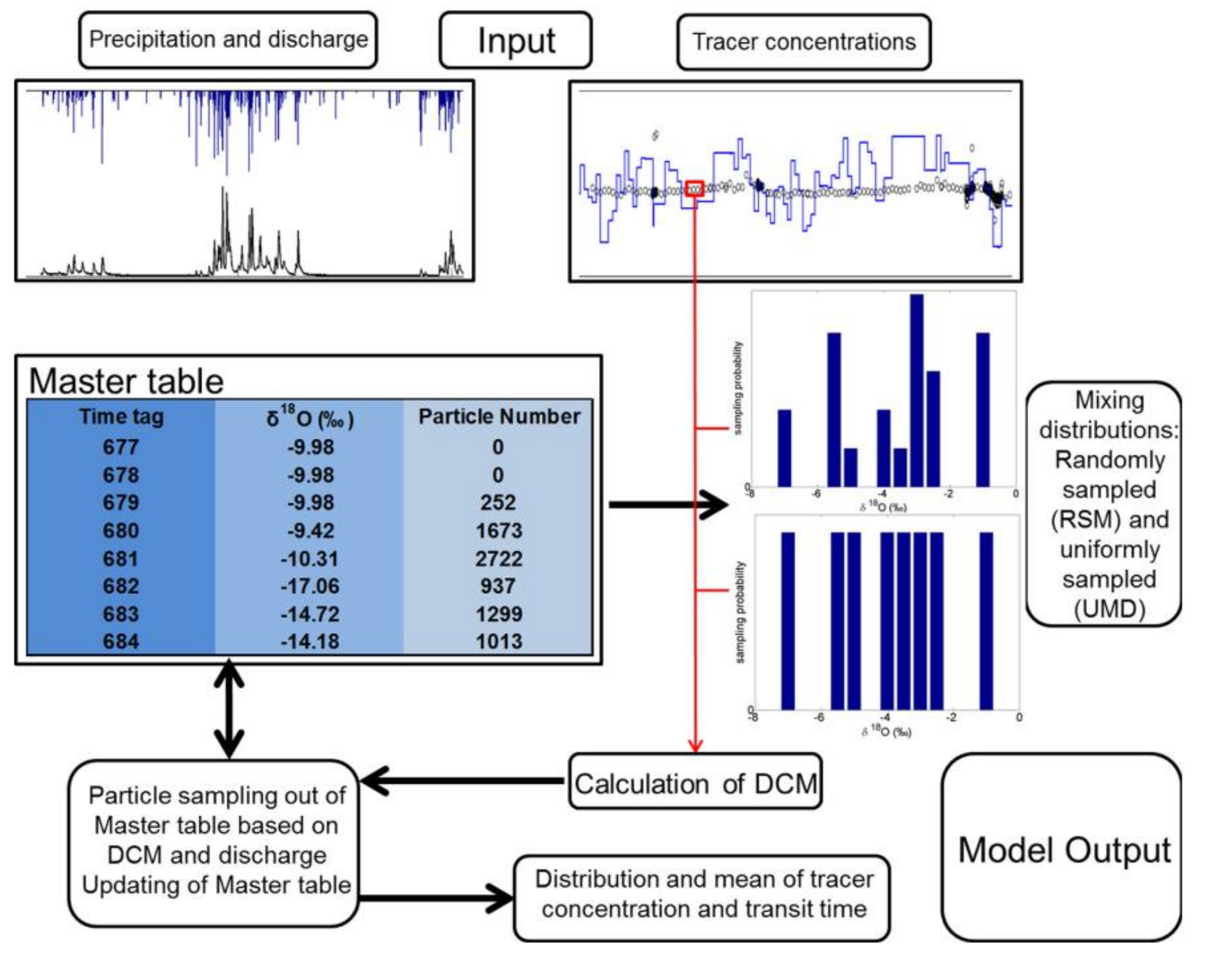


(Figure 0. Three stable Isotopes of Water) (based on Hoefs 1997 and Coplen et al. 2000).

The stable isotopes of water molecules are added naturally to a catchment through precipitation and snowmelt events, and all behave identically within a watershed. Each specific precipitation event has its own unique isotopic signature (fingerprint), which is represented by the corresponding relative concentrations/ratios of the various isotopes. The specific concentration of isotopes in a rain event is dependent on the source and processes undergone prior to the precipitation event.

Isotopic compositions of rainfall can be continuously measured, prior to water entering a catchment (where weather stations exist), and the isotopic composition of water exiting a catchment into a body of surface water can as well be analyzed. The water exiting a catchment typically represents water from precipitation events of various sources and ages, which results in an outflow that is a mixture of the multiple signatures of the rain events. The travel time distribution (TTD) serves as a probability density function of travel times and distribution of water traveling through and exiting the catchment from all locations.

Extensive models, such as the one that is utilized within this paper, can be used to account for the effect of catchment mixing (the degree of interconnectivity between subsurface flow paths and storages), variable distributions of flow paths, residence times, and more in order to identify the mean transit time (the amount of time it takes for water to enter and leave a catchment) of water through a catchment or the transit times of specific precipitation events. These details are useful for revealing key properties and functions of a catchment.



Master table

Time tag	$\delta^{18}O$ (‰)	Particle Number
677	-9.98	0
678	-9.98	0
679	-9.98	252
680	-9.42	1673
681	-10.31	2722
682	-17.06	937
683	-14.72	1299
684	-14.18	1013

Figure 1. Conceptual diagram of the approach. The approach uses the input in form of tracer and hydrological time series and combines this with tracking of the stored tracer characteristics and ages. DCM is calculated based on the distribution of tracer concentration and the measured tracer concentration in streamflow. The RSM distribution represents a randomly sampled mixing distribution where particles have the same probability of being sampled, the UMD is a so called uniform mixed distribution, where every occurring tracer concentration has the same probability of being sampled. The value of DCM determines the ratio of sampling between RSM and UMD, and this eventually results in modeled tracer concentration, transit time, and transit time distribution of catchment discharge at every time step.

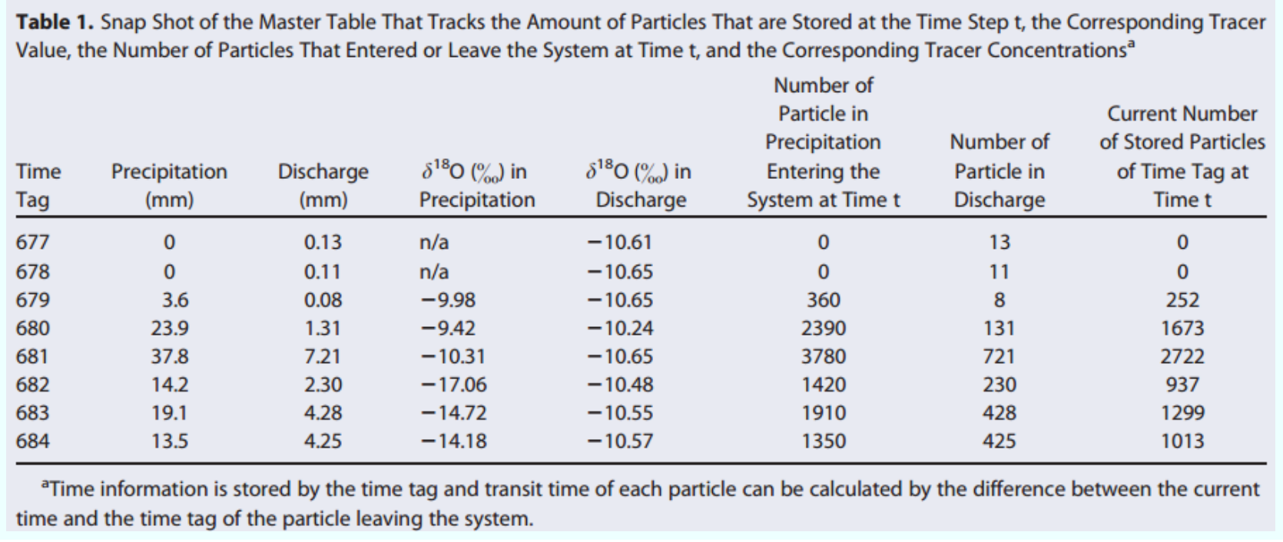


Table 1. Snap Shot of the Master Table That Tracks the Amount of Particles That are Stored at the Time Step t, the Corresponding Tracer Value, the Number of Particles That Entered or Leave the System at Time t, and the Corresponding Tracer Concentrations[a]

Time Tag	Precipitation (mm)	Discharge (mm)	$\delta^{18}O$ (‰) in Precipitation	$\delta^{18}O$ (‰) in Discharge	Number of Particle in Precipitation Entering the System at Time t	Number of Particle in Discharge	Current Number of Stored Particles of Time Tag at Time t
677	0	0.13	n/a	−10.61	0	13	0
678	0	0.11	n/a	−10.65	0	11	0
679	3.6	0.08	−9.98	−10.65	360	8	252
680	23.9	1.31	−9.42	−10.24	2390	131	1673
681	37.8	7.21	−10.31	−10.65	3780	721	2722
682	14.2	2.30	−17.06	−10.48	1420	230	937
683	19.1	4.28	−14.72	−10.55	1910	428	1299
684	13.5	4.25	−14.18	−10.57	1350	425	1013

[a] Time information is stored by the time tag and transit time of each particle can be calculated by the difference between the current time and the time tag of the particle leaving the system.

2 Introduction

In this study, researchers utilized stable isotope data to model and help gather a better understanding of time variant transit time distributions with a new theoretical approach. The approach utilizes isotopic tracer data sets (isotopic compositions of precipitation and discharge over time), and incorporates time variant catchment mixing and other relevant factors to identify the relative times which specific bodies of water (with particular fingerprints) enter and exit the catchment. Their general approach can be identified in Figure 1 on the bottom left. A detailed description of how the model approach incorporated various dependent parameters affecting the time variant transit time distributions can be identified in the 4 equations in 3a below.

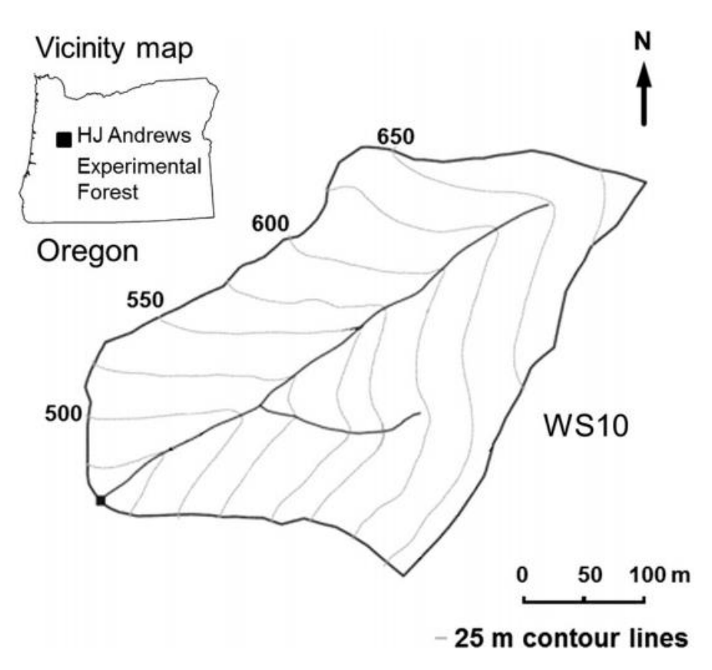


Figure 3. Map of Watershed 10 (WS10) of the H.J. Andrews Experimental forest and the location within Oregon, USA.

The researchers first use this model approach with artificial data as proof of concept of the model's effectiveness. In their proof of concept, the authors demonstrate that the model can very accurately estimate time variant transit times when a time series of the isotopic composition of precipitation events and discharge fluxes are known. This proof Of concept can be seen in Figure 5, where the model was seen to have effectively reproduced the observed time series in a reverse-modeling test.

After proof of concept, the researchers utilized the model with field data from the well-studied H.J. Andrews Watershed 10 (WS10) in NW Oregon (see Figure 3) to determine time variant catchment properties.

3a Methods

The degree of catchment mixing ($DCM(t)$) is calculated at time step t based on equation (1). The concentration C at time step t is:

$$C(t)=DCM(t)\times mRSM(t)+[1-DCM(t)]\times mUMD(t) \tag{1}$$

where $C(t)$ is the tracer concentration at time t as a mixture of $mRSM(t)$, the mean tracer concentration of the randomly sampled mixing distribution of all stored particles at time t, and $mUMD(t)$ the mean tracer concentration of the uniform distribution of all stored particles at time t.

$DCM(t)$ is constrained between 0 and 1, where 1 denotes randomly sampled mixing and 0 denotes incomplete mixing in the catchment (all particles are sampled out of UMD). Equation (1) is solved for $DCM(t)$ at every time step, resulting in a vector of the length t. At every time step, $DCM(t)$ times N particles are drawn from the RSM distribution and 1-$DCM(t)$ times N particles are sampled from the UMD distribution out of all stored particles. The modeled tracer concentration in the stream at time step t, $C_{mod}(t)$, is calculated as follows:

$$C_{mod}(t)=\frac{1}{N}\sum_{i=1}^{N}C_i(t) \tag{2}$$

where N is the total number of particles leaving the catchment via discharge, and $C_i(t)$ is the tracer concentration of each individual particle i that is leaving the catchment at time t.

The time variant transit time of the catchment at time, $tvTT(t)$, is:

$$tvTT(t)=\frac{1}{N}\sum_{i=1}^{N}tt_i(t) \tag{3}$$

The transit time distribution $ttD(t)$ is conditional on the exit time, and is the empirical probability density function of all tt_i leaving the catchment at time step t [*Rinaldo et al.*, 2011]. Furthermore, the model allows calculation of the transit time distribution conditional to a recharge event at time step t, as soon as all particles of a recharge event leave the catchment. The Master Transit Time Distribution (MTTD) is also considered by following *Heidbüchel et al.* [2012]. At time step t the MTTD) (conditional on the exit time) is constructed by superimposing all individual transit time distributions $ttD(t)$, to give one empirical density function:

$$MTTD=\sum_{t=1}^{T}ttD(t) \tag{4}$$

where T is the end of the simulated period and $ttD(t)$ the observed transit time distribution at time step t.

3b Methods

For the field study, data of the isotopic compositions of precipitation events in the (WS10) watershed were gathered from a local weather station. These data of the volume and frequency/occurrence of precipitation, calculated discharge, and measurements of the isotopic compositions of the discharge were collected frequently over the course of two years (2001 – 2003). Data was used to construct time series of stable isotopes in precipitation and streamflow over the time interval. This data is presented in Figure 4.

Time series data was dissected with the use of the model approach algorithm to generate estimates of the time series of the heavy stable isotope of Oxygen and the time variant transit times. Resulting estimates from the model can be identified in Figure 6.

4 Results

The mean transit time was determined to be 415 days (identified by the red line in Figure 10). It was determined that 50% of the water had left the catchment after 329 days, and 90% had left after 1049 days.

In addition to providing an estimate of the mean transit time, the approach was indicated to have been effective in determining time variant transit time of WS10 given the precipitation and stable isotope time series data. This showed how wet periods with high flows had clearly shorter transit times as compared to low flow periods. This can be identified in Figure 7 (and precipitation events of Figure 4), where we see that transit time increased throughout the dry summer periods, reaching a maximum around November to December, after which point the transit time decreases rapidly. This indicates that a significant portion of water that entered the catchment during the later portion of the wet periods and stayed within the catchment throughout the majority of the dryer periods - becoming progressively older. This water is seen to be flushed out rapidly during the period of high precipitation (December – April), to be replaced with younger water through recharge events.

The approach model was seen to as well allow for examinations of the relative ages of water from different sources that are present in the catchment at a given time. We can see this in Figure 7, where we are provided with the probability density of different aged water within the catchment at four different times. This offers valuable insight as to what specific water may be present within the catchment at a given time.

Also, the model was able to infer the transit times of individual rain events in the stream water sample – conditional to the exit time. An example of this is shown in Figure 11, where two specific precipitation events are identified, and the time at which they are projected to leave the catchment is indicated. We may see that for a rain event occurring in October, the majority of water leaves the system within a short period of time (a low transit time). Comparatively, we see that the rain much of the precipitation from the event occurring in April resides within the catchment for a much longer time (a high transit time), and persists throughout the dry season until being flushed in the onset of a wet period.

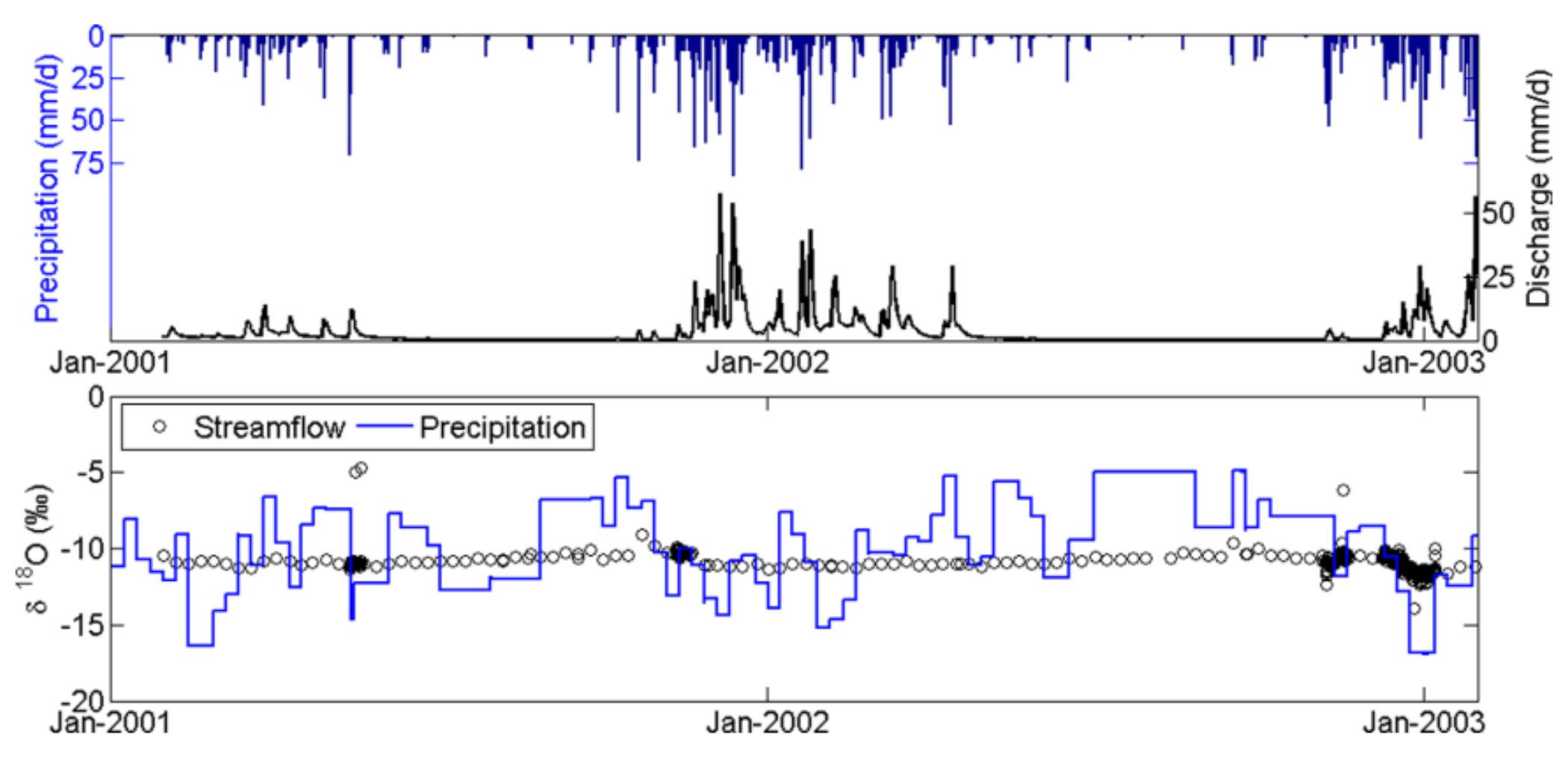


Figure 4. (top) Daily precipitation and daily discharge of WS10, and (bottom) observed streamflow and precipitation ^{18}O signal.

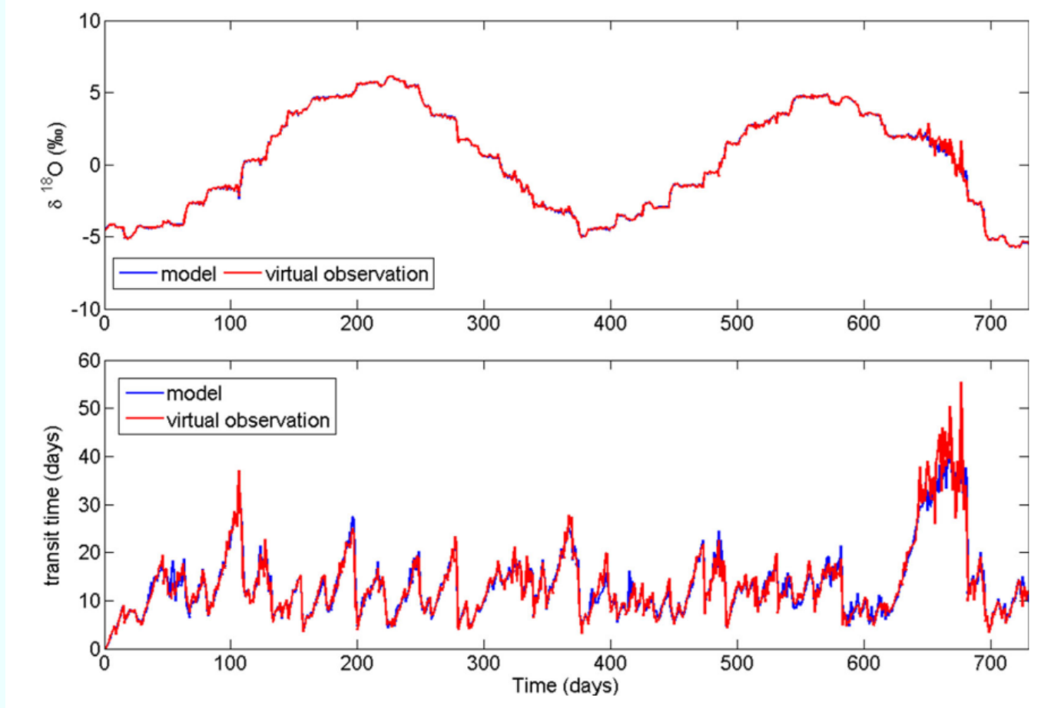


Figure 5. Results of the proof of concept. (top) Modeled and observed artificial ^{18}O time series and (bottom) model and observed/known time variant transit time.

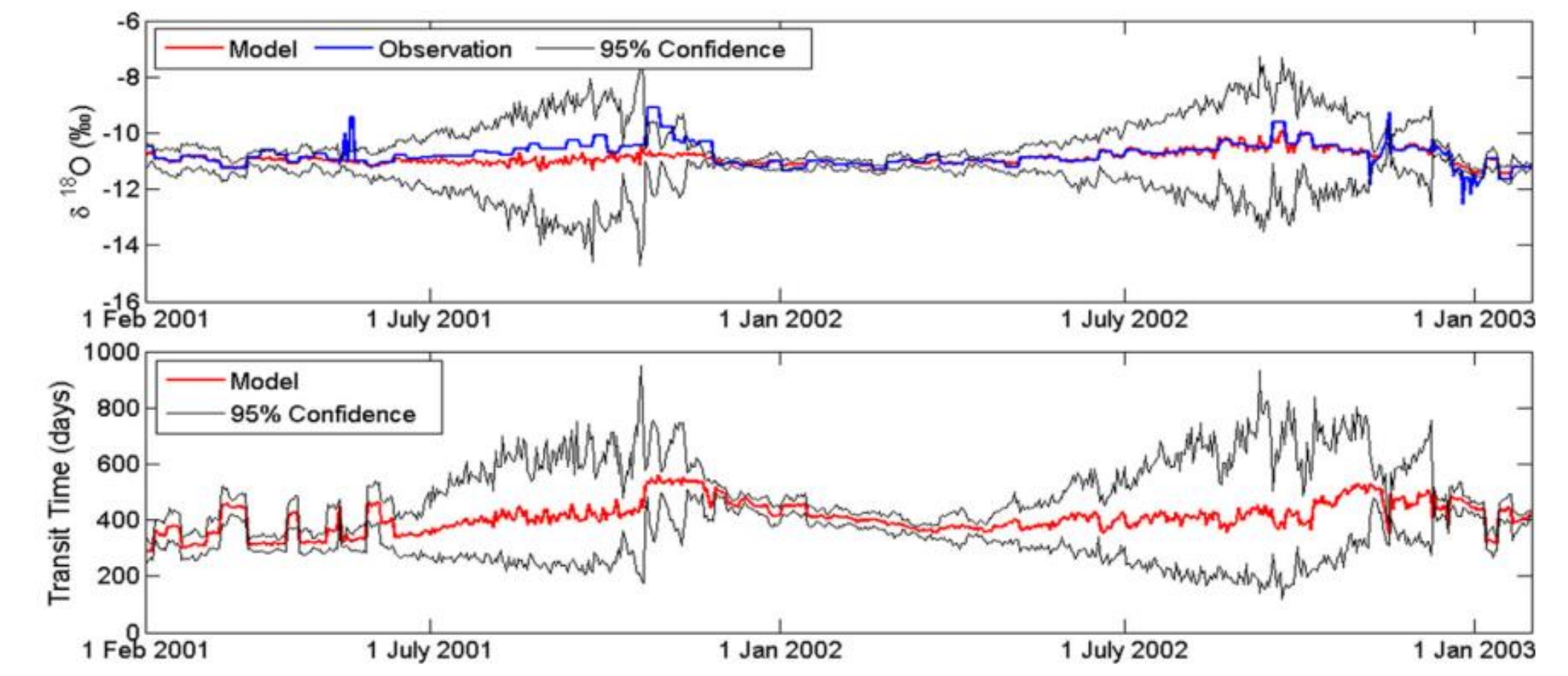


Figure 6. (top) Observed and modeled ^{18}O time series in WS10, including the 95%-confidence bounds of the model results, and (bottom) the modeled time variant catchment transit time and the 95%-confidence bounds.

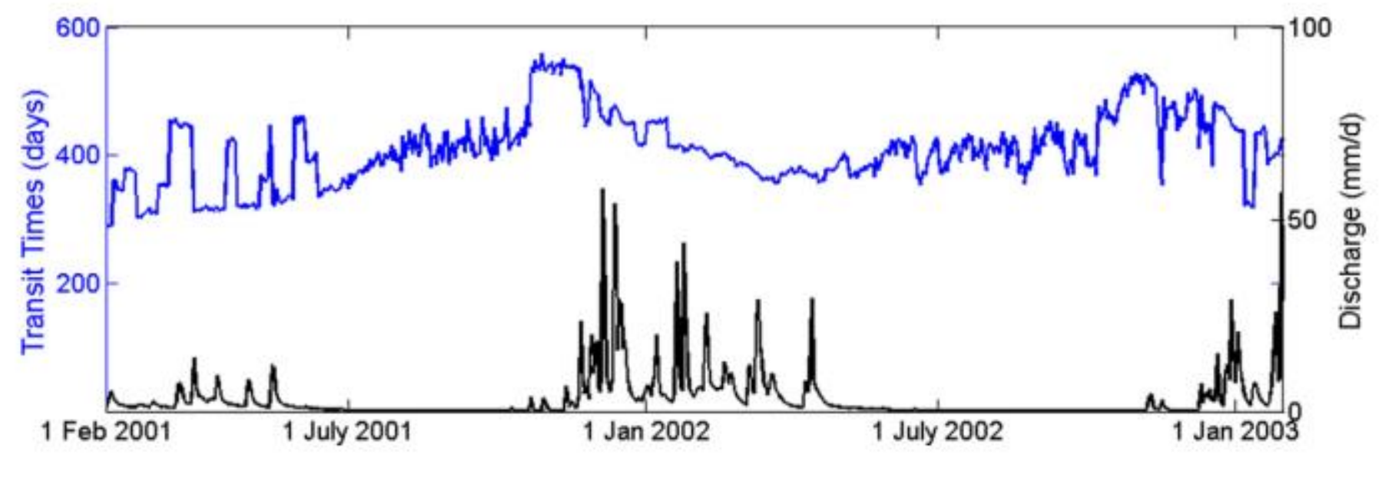


Figure 7. Discharge (black) versus catchment transit time (blue) in WS10.

5 Discussion

The authors note that their model is somewhat limited, and accounting for evapotranspiration fluxes pose an ongoing challenge. They indicate that further studies are needed that can account for more complex representations of catchment structure, and to compare different catchment characteristics and their influence on the mean transit time distribution.

From the results, we see that the researchers' model approach involving the use of stable isotope data sets provides multiple levels of insight regarding the properties and functions of the particular watershed. When this approach is further developed and applied to other watersheds, the resulting information can provide hydrologists with a much deeper understanding of the nature of catchment properties than has ever been achievable prior to this point. This expanded knowledge of the properties and functions of watersheds may be vital for water resource preservation and quantification, contamination remediation, ecological studies, and a variety of other practical applications.

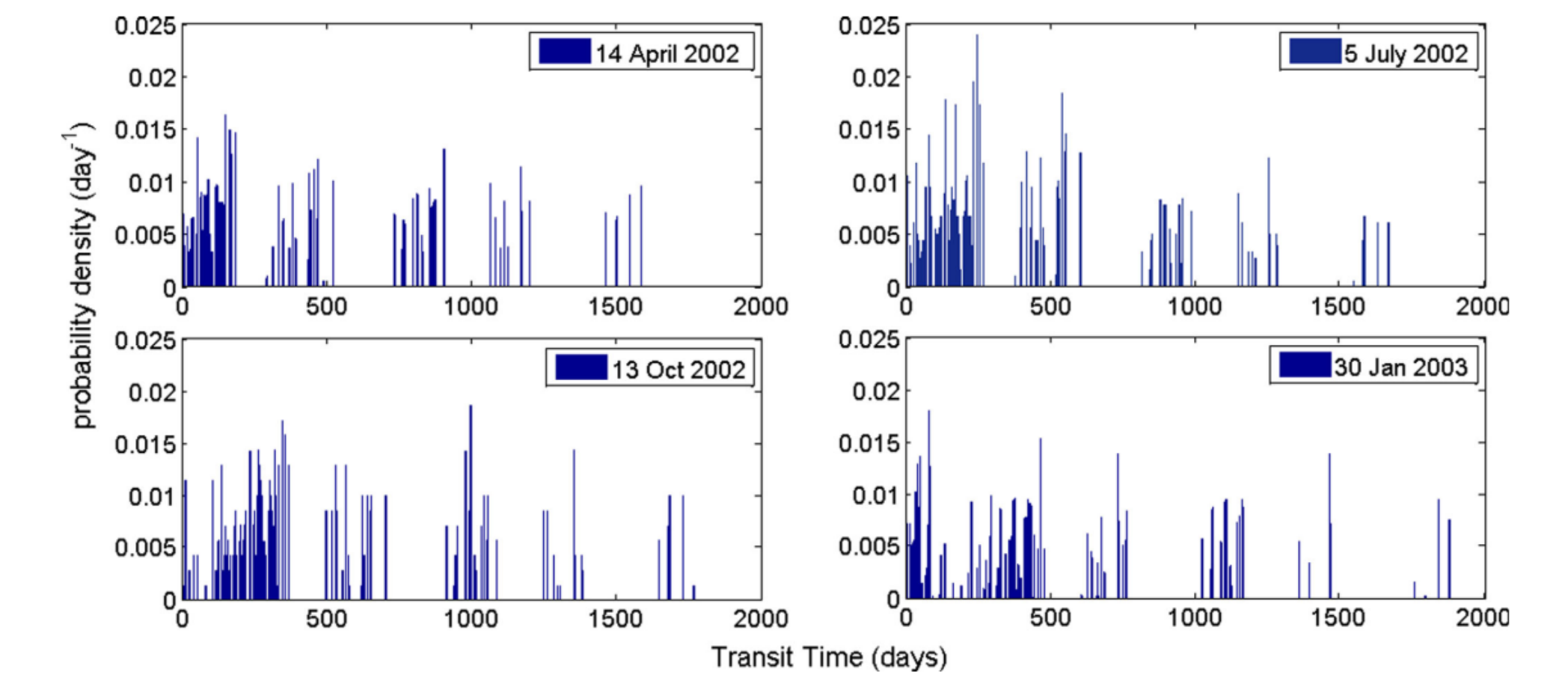


Figure 9. Transit time distribution (conditional to the exit time) at 4 days during the observation period in WS10. The probability density represents the distinct fraction of transit time in streamflow at the respective date. The four different times represent different flow stages with differences in the transit time distribution.

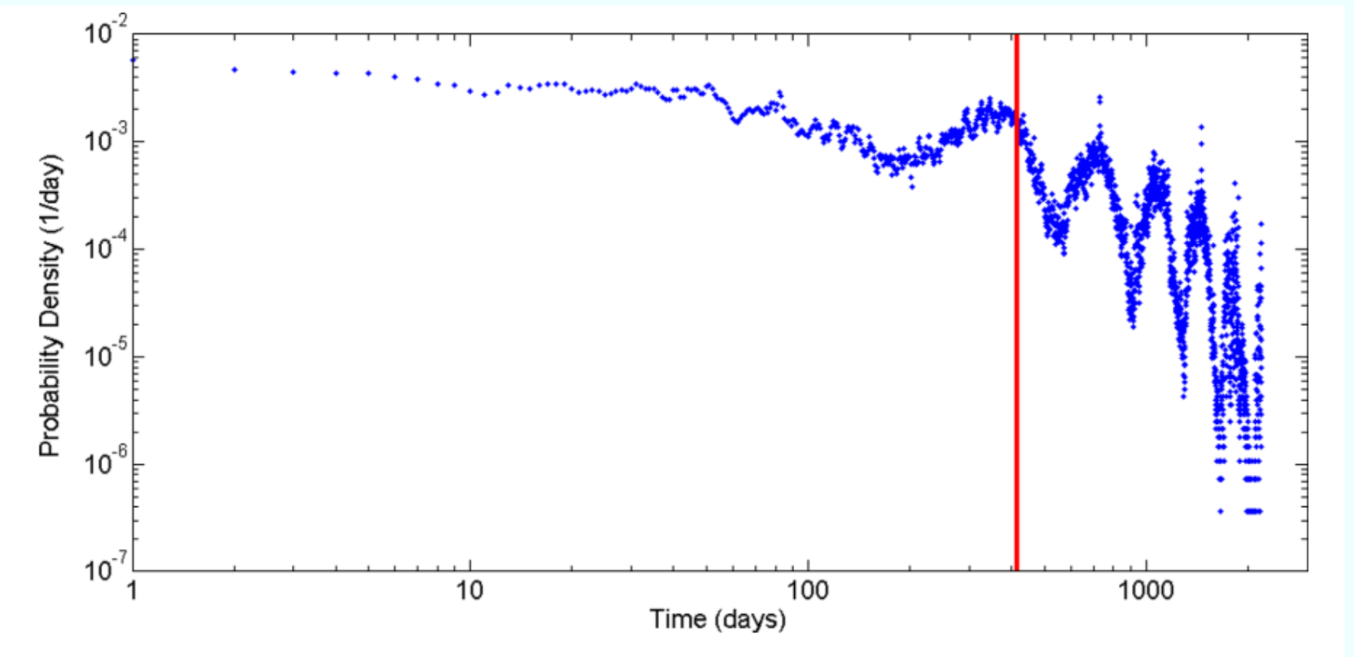


Figure 10. Master transit time distribution (conditional to the exit time) of the available data set in WS10. The red line indicates the mean transit time of WS10.

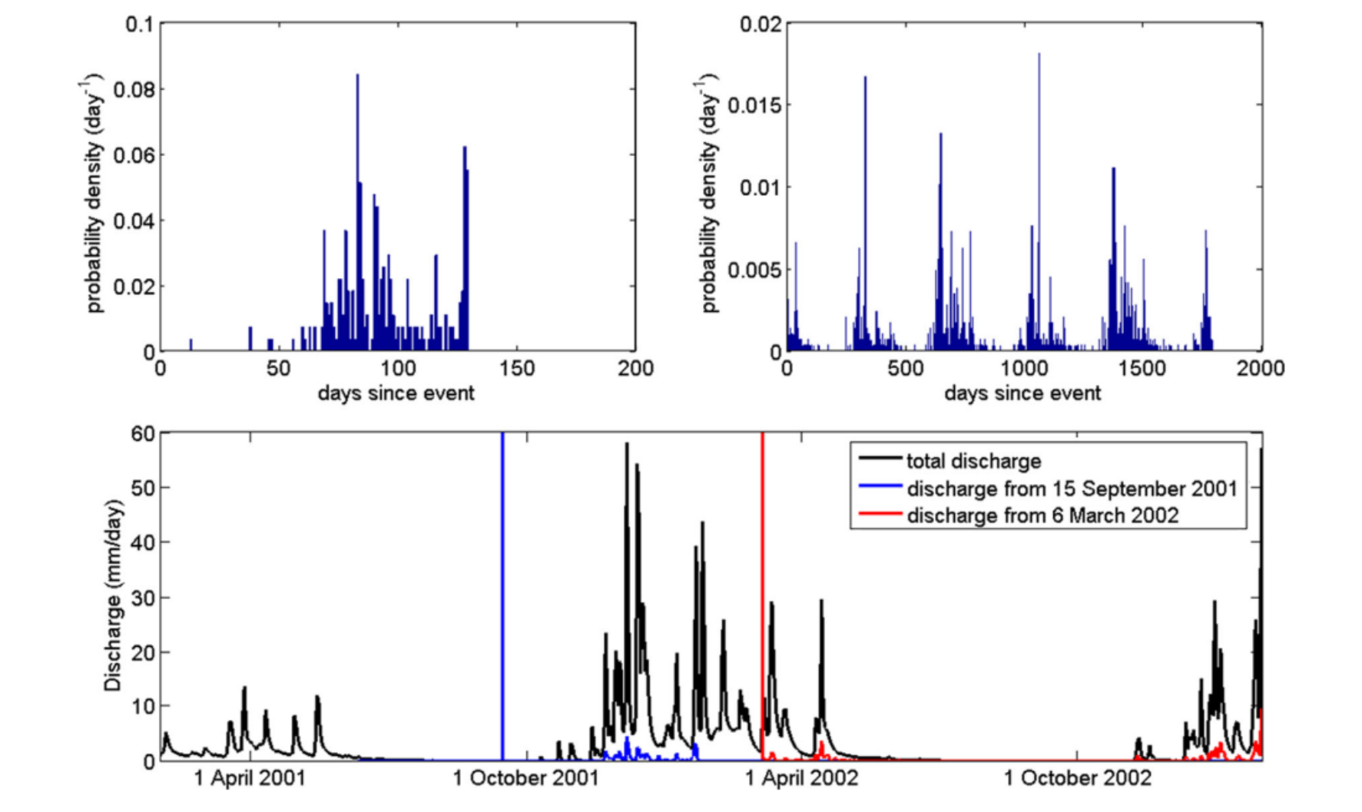


Figure 11. Transit time distributions (conditional to injection time) for two rainfall events in HJA WS10. (top) (left) The probability density function (15 September 2001) and (right) (6 March 2002). (bottom) How the two precipitation events propagate to discharge (their contribution is scaled by a factor 20) is shown. The vertical lines indicate the point in time of the individual recharge events.

6 Conclusion

This study provides a good example of how the fingerprints of the stable isotopes of water can be used to infer the properties and functions of a catchment. It should be noted that this was not a simple process; yet watersheds are as well not simple, and have perplexed researchers for decades. In this study, a new approach was detailed that was able to determine the time variant transit times of water in a catchment. This provides a data driven tool of immense utility for hydrologists to use to gain a detailed understanding of how a catchment, or other hydrological systems, operate throughout the course of time.

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AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2014WR016247

Key Points:

- Approach for time variant catchment transit time
- Modeling irregular shape of transit time distributions by time variant mixing
- Modeling catchment transit time in WS10 of HJA Forest

Correspondence to:
J. Klaus,
julian.klaus@list.lu

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Temporal dynamics of catchment transit times from stable isotope data

Julian Klaus[1], Kwok P. Chun[2,3], Kevin J. McGuire[4], and Jeffrey J. McDonnell[2,5]

[1]Environmental Research and Innovation Department, Luxembourg Institute of Science and Technology, Belvaux, Luxembourg, [2]Global Institute for Water Security, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, [3]Department of Geography, Hong Kong Baptist University, Hong Kong, [4]Department of Forest Resources and Environmental Conservation, Virginia Water Resources Research Center, Virginia Tech, Blacksburg, Virginia, USA, [5]School of Geosciences, University of Aberdeen, Aberdeen, UK

Abstract Time variant catchment transit time distributions are fundamental descriptors of catchment function but yet not fully understood, characterized, and modeled. Here we present a new approach for use with standard runoff and tracer data sets that is based on tracking of tracer and age information and time variant catchment mixing. Our new approach is able to deal with nonstationarity of flow paths and catchment mixing, and an irregular shape of the transit time distribution. The approach extracts information on catchment mixing from the stable isotope time series instead of prior assumptions of mixing or the shape of transit time distribution. We first demonstrate proof of concept of the approach with artificial data; the Nash-Sutcliffe efficiencies in tracer and instantaneous transit times were >0.9. The model provides very accurate estimates of time variant transit times when the boundary conditions and fluxes are fully known. We then tested the model with real rainfall-runoff flow and isotope tracer time series from the H.J. Andrews Watershed 10 (WS10) in Oregon. Model efficiencies were 0.37 for the ^{18}O modeling for a 2 year time series; the efficiencies increased to 0.86 for the second year underlying the need of long time tracer time series with a long overlap of tracer input and output. The approach was able to determine time variant transit time of WS10 with field data and showed how it follows the storage dynamics and related changes in flow paths where wet periods with high flows resulted in clearly shorter transit times compared to dry low flow periods.

1. Introduction

Understanding the velocities, celerities, and transit time distributions of the headwater hydrograph is a community challenge [*McDonnell and Beven*, 2014]. We now know that the time that it takes water particles to travel through a catchment to a stream is different to the celerity that yields the hydrograph dynamics, often observed as a fast responding hydrograph that mainly consists of old water [*Kirchner*, 2003]. Transit time, the time water particles take to travel through the catchment, is therefore a fundamental descriptor of catchment properties [*McDonnell et al*., 2010]. Mean transit times (MTT) and the transit time distributions (TTD) (also referred to as the probability density function (pdf) of transit times) integrate catchment flow path variability, and the combined effects of water storage and fluxes as water is transported through catchments [*Broxton et al*., 2009; *Botter et al*., 2010; *Benettin et al*., 2013a, 2013b]. The traditional approach for quantifying MTT and TTD of catchments is via the convolution integral that relates the input and the output of a measured conservative tracer time series with a transfer function that determines the shape of the TTD (for review see *McGuire and McDonnell* [2006]). While many studies have applied this approach since the pioneering work of *Dincer et al*. [1970] and *Maloszewski and Zuber* [1982], recent papers have commented on the assumptions and highlighted the limitations of the technique [*Hrachowitz et al*., 2010; *Botter et al*., 2010; *Rinaldo et al*., 2011].

The main limitation with the standard convolution approach, as noted first by *Niemi* [1977] and restated more recently by *Hrachowitz et al*. [2013], is that convolution usually does not account for the temporal dynamics of water flow paths and their changing distributions through time, by simplifying the system to a time invariant one. Time variance in the TTD has become the focus of recent studies [e.g., *van der Velde et al*., 2010; *Botter et al*., 2010, 2011]—the consensus is that the assumption of time invariance will lead to unrealistic representations of MTT [*Rinaldo et al*., 2011].

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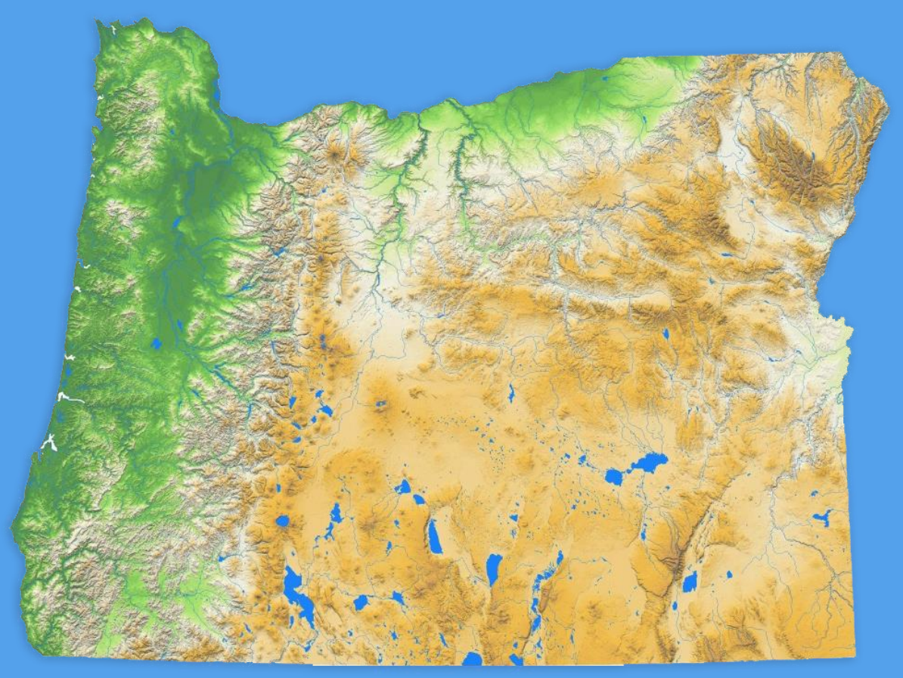
Changing Climate and Willamette Valley Snowmelt

Makani Stormont , Earth and Physical Sciences Department, Western Oregon University, Monmouth, Oregon, 97361



Abstract

This poster will investigate the effects of warming temperature on the maritime snowpack of primarily the McKenzie River Basin (MRB), but can be applied to the Willamette Valley as a whole. Simulations on the distribution of Snow Water Equivalent (SWE) in the MRB for the period of 1989-2009 have shown a frightening result when combined with a projected 2 ◦C increase in temperature and a ±10 % variability in precipitation. Overall SWE storage in the MRB is predicted to decrease by 56% with the increase in temperature. Also this would shift the average date of peak snowpack 12 days earlier With such a huge loss in volume of SWE, typical summertime snowmelt from the mountains will be significantly less. Research of his kind will be imperative in accommodating to the water needs of the region in the future. SWE modeling and data collection was done by Sproles, Nolin, Rittger, and Painter in their paper "Climate Change Impacts on Maritime Mountain Snowpack in the Oregon Cascades".

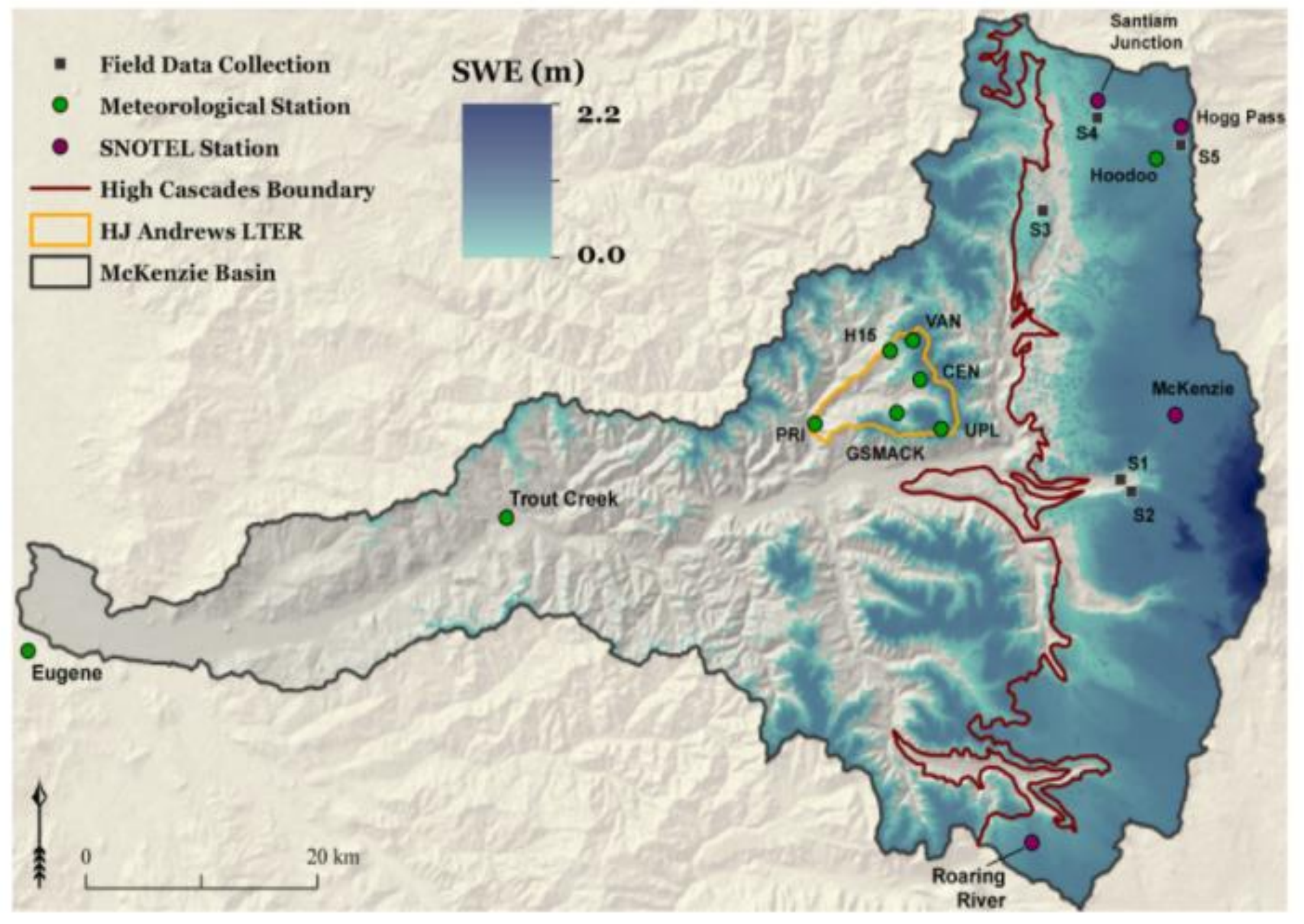


Fig. 1 Image of McKenzie River Basin, the primary area of study. Simulated SWE for reference conditions.

Introduction

Even winter-low temperatures in the Pacific Northwest don't get very far below freezing. Snow in the Western Cascades exists at temperatures dangerously close to melting. For this reason, global climate change poses a serious threat to the snowpack storage capabilities in elevation ranges of about 1000-2000m and thus a threat to everything and everyone that relies on this melt.

Maritime snowpack provides melt water for ecosystems, agriculture, municipalities, and recreation –especially in summer when demand is higher and precipitation reaches a minimum. This problem is not unique to the Oregon Cascades and is of significance globally, massive populations around the world relying on maritime snow will have diminishing supply of water available in the summer months.

Methods

Sproles and his team make use of tool known as SnowModel to simulate meteorological and snow conditions throughout the McKenzie River Basin. SnowModel is able to simulate a complex environment of temperature, precipitation, slope, land cover and the full winter season evolution of SWE including accumulation, canopy interception, wind redistribution, sublimation/evaporation, and melt with a high degree of accuracy. The reference data for this model are the air temperature, precipitation, relative humidity, wind speed, and wind direction records of 10 different weather stations throughout the 3041 sq. km MRB from 1989-2009. To determine the response of snowpack to increased temperature and changes in precipitation, analysis was conducted in three parts. The first part, T2 increases all temperatures recordings 1989-2009 by 2 ◦C and runs it through SnowModel. The second and third parts also increase the temperature by 2 ◦C but also add either a 10% increase in precipitation (T2P10) or a 10% decrease in precipitation (T2N10).

Results

Under the conditions of T2 mean peak SWE for the basin decreased by an average of 56 % for the study period. This equates to a decrease from normal of about 0.70 cubic kilometers of SWE. The increase of precipitation in T2P10 leads to a mean peak SWE loss of 0.62 cubic kilometers, decrease in precipitation in T2N10 yields a decrease 0.78 cubic kilometers. Elevations below 1300 m show a substantial loss of SWE accumulation, elevations around 1500 m sill sustain heavy snow loss, but still retain a seasonal snowpack with distinct accumulation and ablation periods (all scenarios). spring and properly into the winter (before the vernal equinox). The average date for simulated peak SWE in the MRB during the study period is 31 March. However, in T2 the average date for peak SWE shifts 12 days earlier in the water year. This number is 22 days in T2N10 and 6 days in T2P10. The elevation band of 1000m-1500m generated 53 % of the basin-wide losses of SWE in the T2 scenario, and comprises 45 % of the basin area.

Discussion

As expected, simulating a climate similar to what we are expecting in the coming decades results in a devastating blow to the amount of water stored as snow for the summers. The 1000-1500m elevation range changes to a rain dominated area after the 2 ◦C increase and the snowpack that would linger there for months is instead immediately beginning its journey to the valley. The MRB will increasingly experience more precipitation falling as rain rather than snow in warmer conditions. This will greatly alter the timing of seasonal runoff which is sure to have wide reaching consequences for all aspects of life in the region.

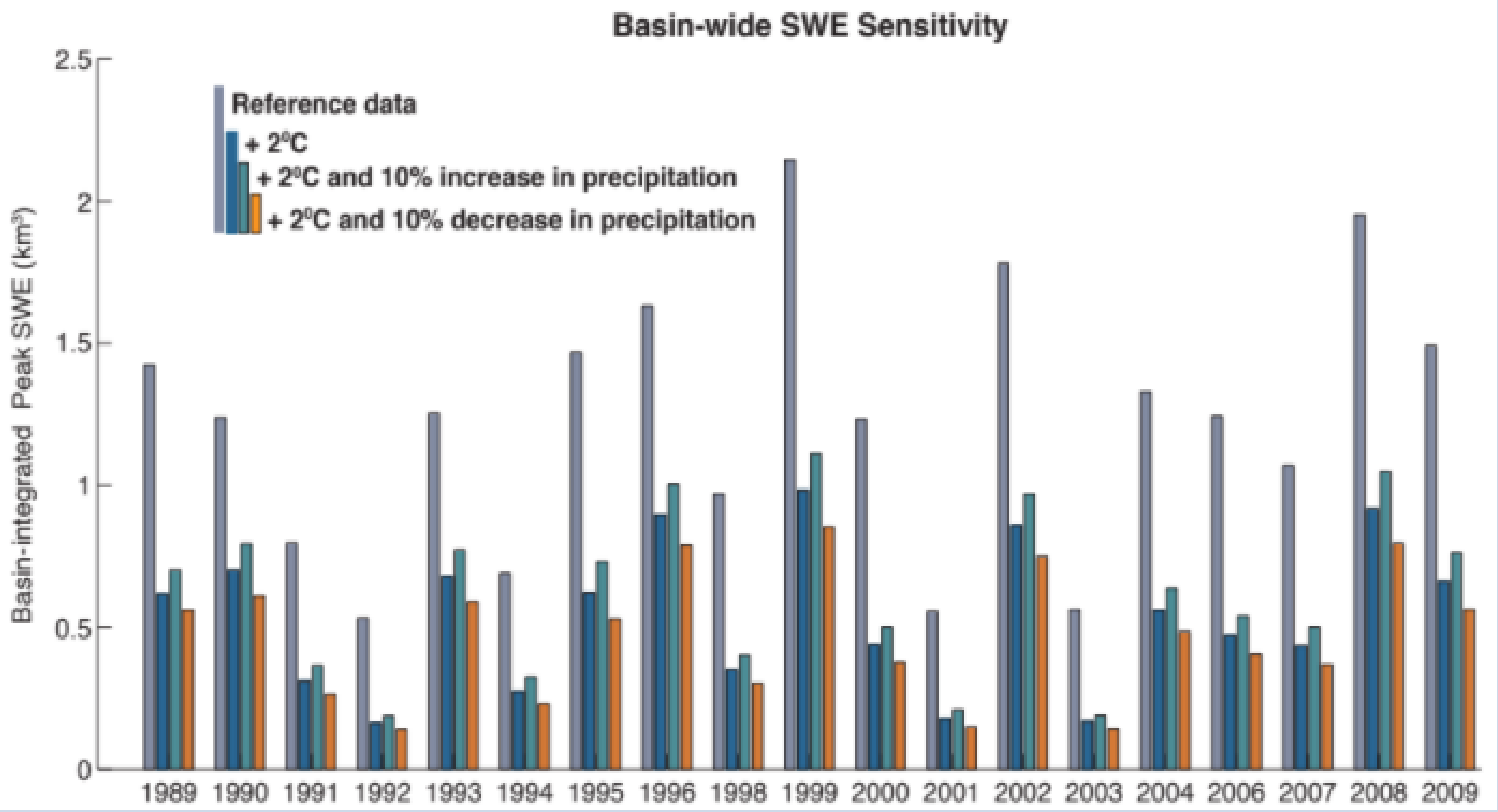


Fig. 2 Peak SWE volume integrated over area of MKB with response to temperature and precipitation changes.

Discussion (cont.)

The amount of SWE volume lost (0.70 cubic kilometers) is more than twice the size of the largest impoundment in the basin (Cougar Reservoir). A drop this large scaled up to the entirety of Western Oregon in addition to the booming population of the area may lead to water shortages for large amounts of people.

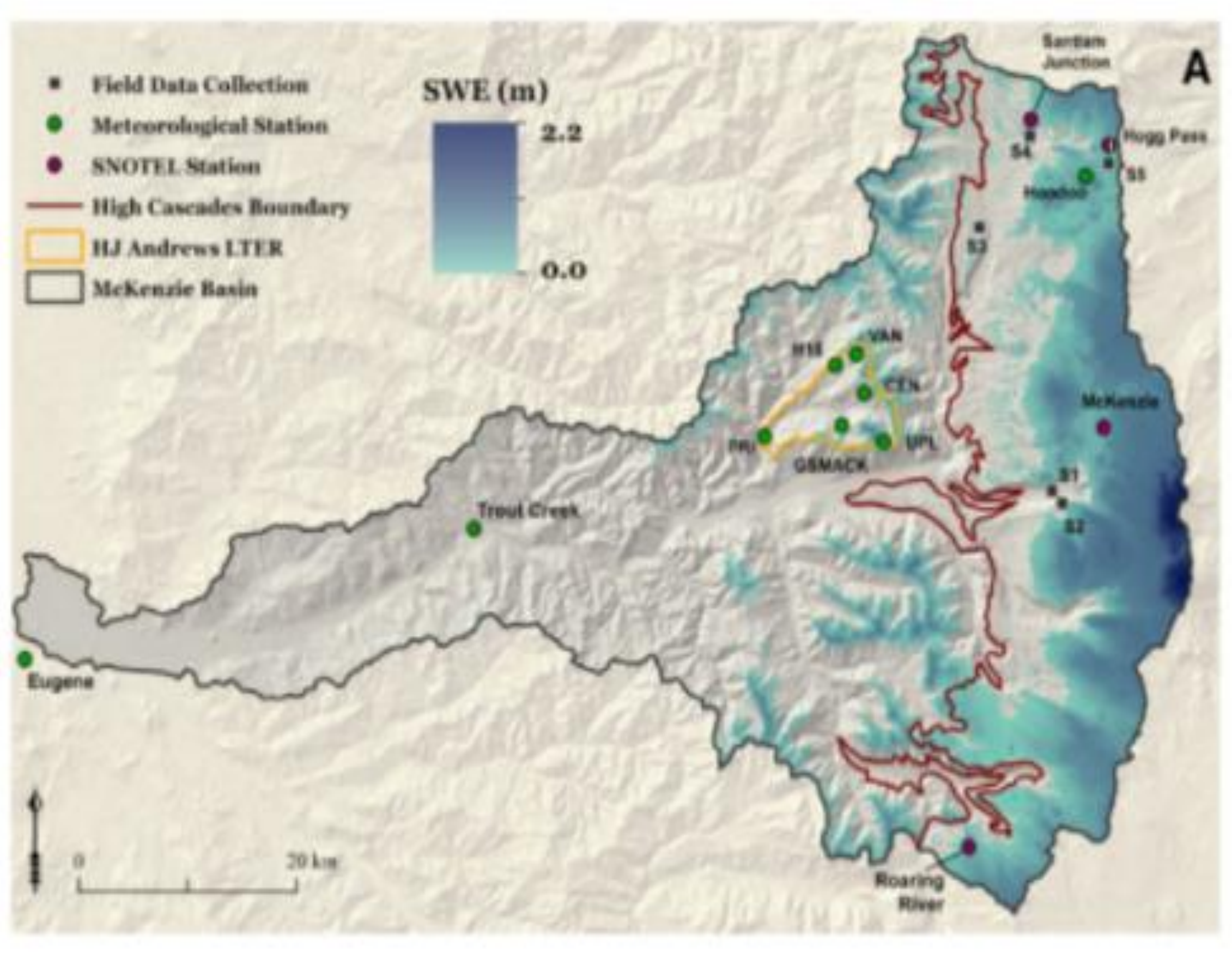


Fig. 3 Simulated SWE in scenario T2 for comparison to Fig. 1.

Conclusion

Because maritime snow accumulates at temperatures close to 0 ◦C, the seasonal accumulation and ablation of maritime snow is sensitive to temperature. Although this study focused on a single watershed, the processes affecting snowpack in the McKenzie River are similar to other maritime snowpacks across the Earth .Research such as this is vital to bettering water management strategies and preparing for long-term changes to our climate. Computer simulations like the one used here will be critical in predicting the oncoming changes to our hydrologic cycle in Oregon and understanding the mechanisms by which warming will effect maritime snowpack.

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Climate change impacts on maritime mountain snowpack in the Oregon Cascades

E. A. Sproles[1,*], **A. W. Nolin**[1], **K. Rittger**[2], **and T. H. Painter**[2]

[1]College of Earth, Ocean, and Atmospheric Sciences, 104 CEOAS Administration Building, Oregon State University, Corvallis, OR USA 97331-5503, USA
[2]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA USA 91109, USA
[*]currently at: National Health and Environmental Effects Research Laboratory, US Environmental Protection Agency, Corvallis, OR, USA

Correspondence to: E. A. Sproles (eric.sproles@gmail.com)

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Abstract. This study investigates the effect of projected temperature increases on maritime mountain snowpack in the McKenzie River Basin (MRB; 3041 km^2) in the Cascades Mountains of Oregon, USA. We simulated the spatial distribution of snow water equivalent (SWE) in the MRB for the period of 1989–2009 with SnowModel, a spatially-distributed, process-based model (Liston and Elder, 2006b). Simulations were evaluated using point-based measurements of SWE, precipitation, and temperature that showed Nash-Sutcliffe Efficiency coefficients of 0.83, 0.97, and 0.80, respectively. Spatial accuracy was shown to be 82 % using snow cover extent from the Landsat Thematic Mapper. The validated model then evaluated the inter- and intra-year sensitivity of basin wide snowpack to projected temperature increases (2 °C) and variability in precipitation (±10 %). Results show that a 2 °C increase in temperature would shift the average date of peak snowpack 12 days earlier and decrease basin-wide volumetric snow water storage by 56 %. Snowpack between the elevations of 1000 and 2000 m is the most sensitive to increases in temperature. Upper elevations were also affected, but to a lesser degree. Temperature increases are the primary driver of diminished snowpack accumulation, however variability in precipitation produce discernible changes in the timing and volumetric storage of snowpack. The results of this study are regionally relevant as melt water from the MRB's snowpack provides critical water supply for agriculture, ecosystems, and municipalities throughout the region especially in summer when water demand is high. While this research focused on one watershed, it serves as a case study examining the effects of climate change on maritime snow, which comprises 10 % of the Earth's seasonal snow cover.

1 Introduction

1.1 Significance and motivation

The maritime snowpack of the Western Cascades of the Pacific Northwest (PNW) United States is characterized by temperatures near 0 °C throughout the winter and deep snow cover that can accumulate to 5000 mm deep (Sturm et al., 1995). This important component of the hydrologic cycle stores water during the winter months (November–March) when precipitation is highest, and provides melt water that recharges aquifers and sustains streams (Dozier, 2011) during the drier months of the year (June–September). Because maritime snow accumulates and persists at temperatures close to the melting point, it is fundamentally at risk of warming temperatures (Nolin and Daly, 2006). The McKenzie River Basin (MRB, Fig. 1), located in the Central Western Cascades of Oregon, exhibits characteristics typical of many watersheds in this region, where maritime snowpack provides melt water for ecosystems, agriculture, hydropower, municipalities, and recreation – especially in summer when demand is higher and precipitation reaches a minimum (United States Army Corps of Engineers, 2001; Oregon Water Supply and Conservation Initiative, 2008).

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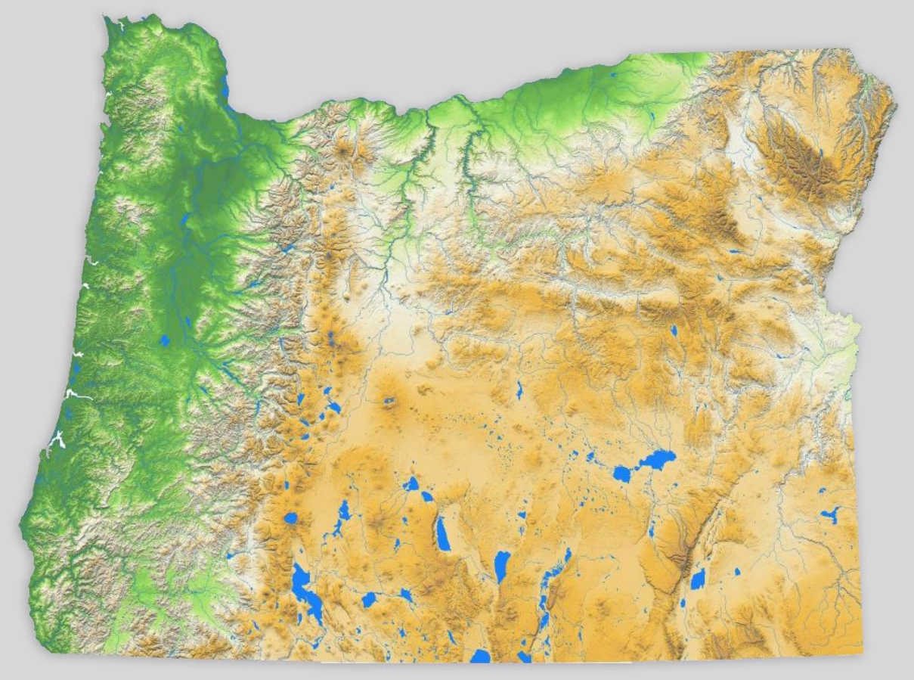
Climate Changes Affect on Mountain Hydrology of Oregon Cascades

Hunter Collins, Earth and Physical Sciences Department, Western Oregon University, Monmouth, Oregon, 97361
email: hcollins14@wou.edu



Abstract

Scientific research has been done that points towards climate change being real and having a very real and adverse effect on many natural environments throughout the world. In our society today we neglect to look at our own local “ice caps”, being snowpacks created in the mountains of our area, specifically the Cascade Range. While focus is on polar ice caps there is a unstudied threat to the local snow packs of many mountains throughout Oregon. Mountain watersheds are considered to be “dynamically vulnerable”, meaning that due to a strong gradient in climate, hydrology, ecosystems, and introducing in human interactions as well, the watershed is much more susceptible to minor changes causing bigger issues. In simpler words the conditions for the snowpacks on mountains to remain snow at the levels they are currently at is much more temperamental than other environments since the nature of snow is very specific for it to be produced and maintained.

Multiple monitoring stations are set up throughout Oregon and the Cascade Range to monitor precipitation as well as stream flow. While these factors are very important for considering a watersheds current activity and potential it does not monitor the snowpacks of the mountainous regions in almost any regard. The systems lack the insight to look at the geology of the area coupled with the vegetation across the watershed and land use, also many other factors below ground that can affect states of the water, stocks, flows and transit time through the watershed. Mountain watersheds are extremely complex to start and in Oregon we add in the non-natural impacts that humans have on the environment to. All of these factors cannot be accounted for and monitored by a single device within a system, there is also interpretation that comes along with the data to see how all of the factors affect each other positively and negatively. In order to predict changes to these environments we need a model that better represents the complexities of the system.

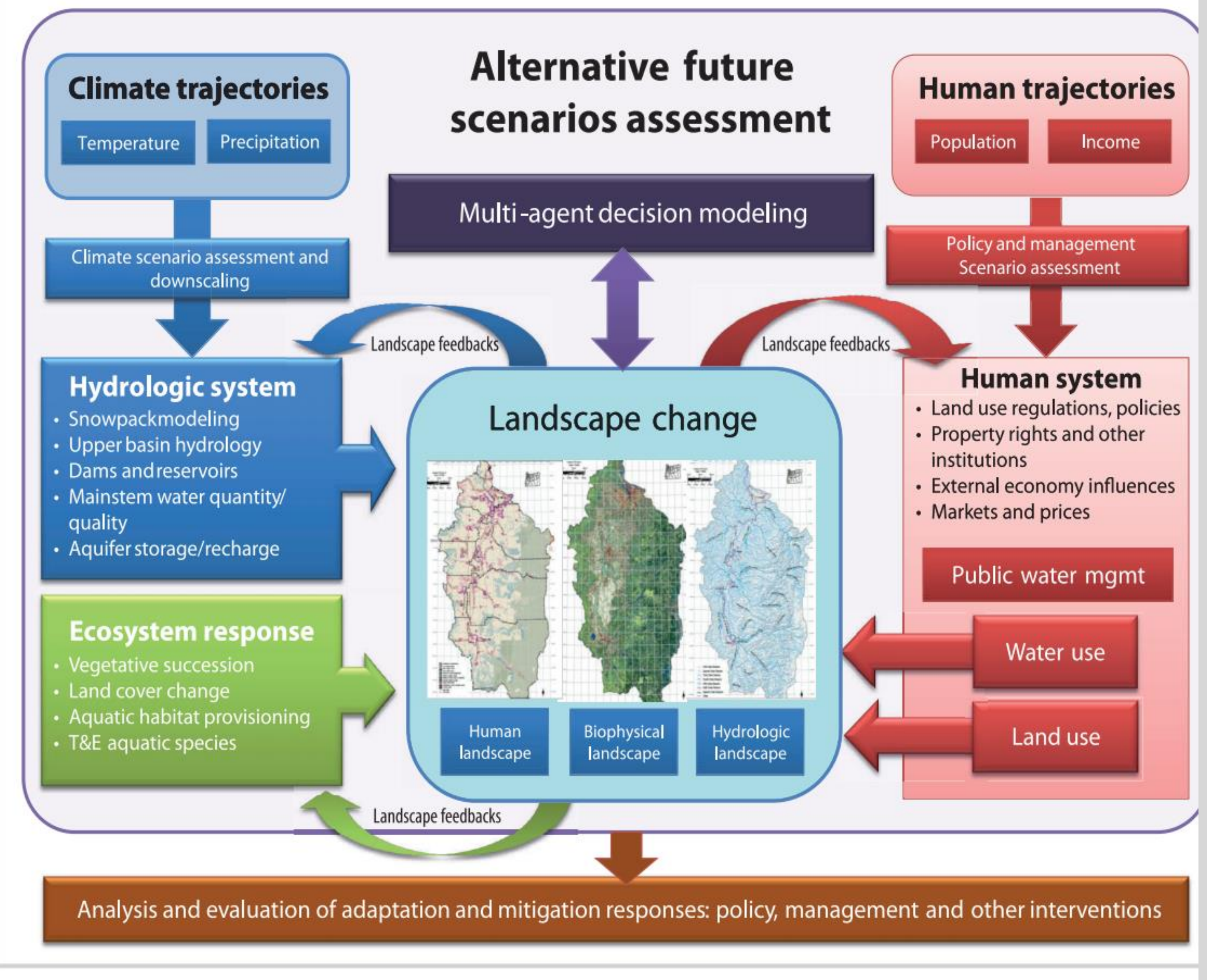
Introduction

The Cascade Range stretches from Northern California up through both Oregon and Washington to just a small portion extended into British Columbia. The Oregon Cascades include mountains like Mt. Hood, Jefferson, the Three Sisters mountains, and Crater Lake Mountain. In the PNW there is approximately 9200 square kilometers of snow, or about 6.5 cubic kilometers of fresh water stored in snow that is considered “at-risk” (Nolin/Daly 2006). Tree cover and how this affects wind patterns through a mountainous region is a impact not considered by most monitoring systems currently in use. Figure 1 (N/D2006) shows what conditions create “at-risk” or maritime snow, due to these conditions the snow is very susceptible to melting or not precipitating as snow if the climate of an area were to be raised by even a small degree due to the complexity of the system.

Envision Model

The closest thing that we have to a overall encompassing model is called the Envision model. This model takes into account future scenarios and how they might affect natural systems as well as societal impacts changes may have. It looks at changes in climate in regards to temperature and precipitation over time and tries to understand how that would affect systems and cycles like the hydrologic. It then looks at the ecosystems responses and how the landscape would change as a result of both the hydrologic system changes and the ecosystem response, including landscape feedbacks that could happen because of these changes. Within “landscape” there are three categories to be considered the human, the biophyscial, and the hydrologic. Human landscape is simply the landscape of occupants throughout a given location. Biophysical landscape would be the vegetation and such that makes up an area and the hydrologic landscape would be the underlying connections through water that can be tracked. The Envision model is a very useful because it also takes into account human impacts and trajectories in the form of human population and income. Changes in these trajectories can lead to changes a few different areas. Water and land use are the biggest impacts from the human side of the board, these two uses can affect the hydrologic cycle in unknown ways and by the time the damage is discovered it could be too late to repair.

The human system experience changes in land use regulations and policies as well as property rights, external economic influences can be accounted for and looked at in this system. Finally and most important to a lot of Americans is changes in the markets and prices for things. Ending the Envision model is the bottom box which is where we take the analysis of all the impacts above and the responses and decide whether there needs to be something done about it. Whether this something be new policies, or management techniques for resources, or if some sort of other intervention is necessary.



Impacts on Humans of Less Snow

With diminishing snow supply and snowpack up on the mountains throughout the Oregon area there would be an overall loss of available fresh water and ski areas. With the rise in temperature resulting in an overall warmer climate this can make the snow at lower elevations melt away. Throughout the Oregon Cascades there are between six and eight ski areas and of those there is only two that are not considered “at-risk” snow areas. Not only will there be less snow in these areas due to the overall climate the amount of “winter” that would be experienced in these areas would significantly decrease. With less of the primetime winters for these ski areas it is a reasonable assumption that they would suffer economically and may have to shut down. The less materialistic view of things would also point out that with less snow on the mountains the reservoir for freshwater being stored as snow is significantly cut down as well.

Our current monitoring systems do not account for all the factors necessary for tracking the climates impact on our overall snowpack levels. Along with this the total understanding of the impact of these diminishing watersheds cannot be fully grasped. Not only must the monitoring system account for all of the factors that can affect the “at-risk” snow, such as what we have here in the Oregon Cascades, it must be able to understand the overall total impact the losses would be for the environment and society.

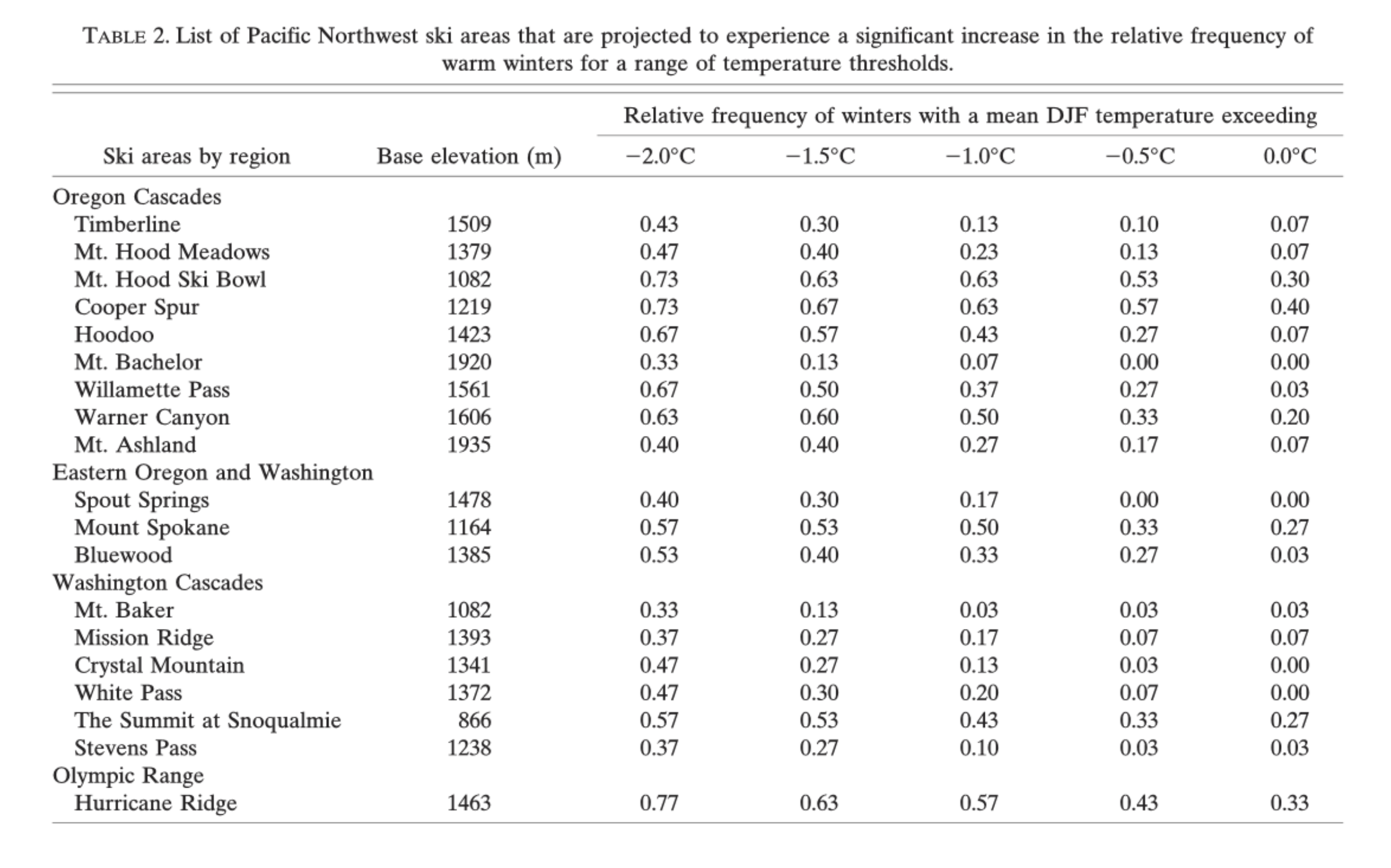


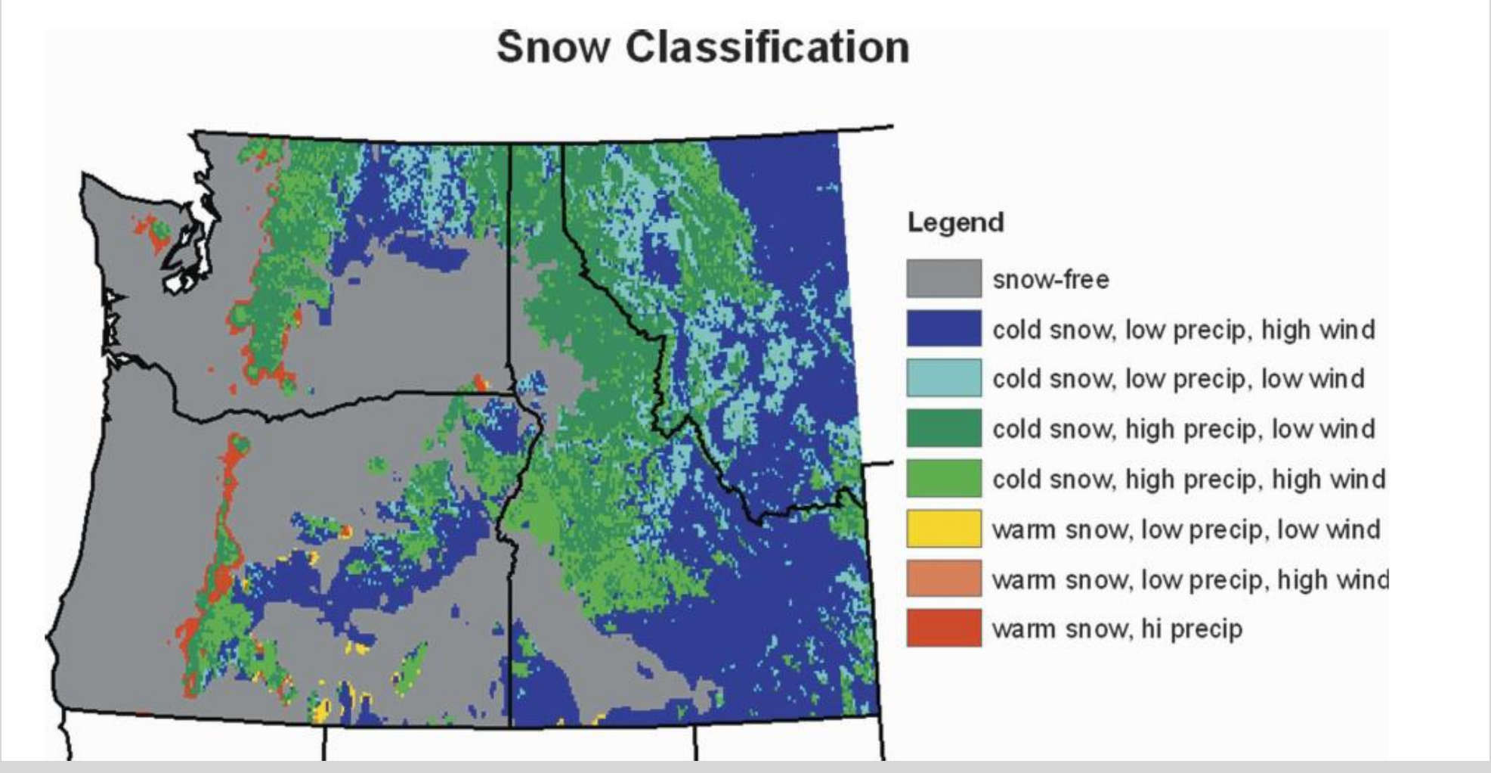
TABLE 2. List of Pacific Northwest ski areas that are projected to experience a significant increase in the relative frequency of warm winters for a range of temperature thresholds.

		Relative frequency of winters with a mean DJF temperature exceeding				
Ski areas by region	Base elevation (m)	−2.0°C	−1.5°C	−1.0°C	−0.5°C	0.0°C
Oregon Cascades						
Timberline	1509	0.43	0.30	0.13	0.10	0.07
Mt. Hood Meadows	1379	0.47	0.40	0.23	0.13	0.07
Mt. Hood Ski Bowl	1082	0.73	0.63	0.63	0.53	0.30
Cooper Spur	1219	0.73	0.67	0.63	0.57	0.40
Hoodoo	1423	0.67	0.57	0.43	0.27	0.07
Mt. Bachelor	1920	0.33	0.13	0.07	0.00	0.00
Willamette Pass	1561	0.67	0.50	0.37	0.27	0.03
Warner Canyon	1606	0.63	0.60	0.50	0.33	0.20
Mt. Ashland	1935	0.40	0.40	0.27	0.17	0.07
Eastern Oregon and Washington						
Spout Springs	1478	0.40	0.30	0.17	0.00	0.00
Mount Spokane	1164	0.57	0.53	0.50	0.33	0.27
Bluewood	1385	0.53	0.40	0.33	0.27	0.03
Washington Cascades						
Mt. Baker	1082	0.33	0.13	0.03	0.03	0.03
Mission Ridge	1393	0.37	0.27	0.17	0.07	0.07
Crystal Mountain	1341	0.47	0.27	0.13	0.03	0.00
White Pass	1372	0.47	0.30	0.20	0.07	0.00
The Summit at Snoqualmie	866	0.57	0.53	0.43	0.33	0.27
Stevens Pass	1238	0.37	0.27	0.10	0.03	0.03
Olympic Range						
Hurricane Ridge	1463	0.77	0.63	0.57	0.43	0.33

Snow Classifications

Snowpacks of mountainous regions can be described based off of a classification tree. The first separation between classifications, when considering snowy areas, is whether there is warm or cold snow. What this means is whether the weather is already very cold conditions that support the snow, like in an arctic area, or a more normalized climate which just supports snow during certain times and conditions, like how snow works in Oregon. The next two breaks are the same for cold or warm snow, they are high/low precipitation and high/low wind speeds in the given environment. Warm snow with high precipitation is considered to be maritime snow, this snow is at a risk for melting due to the warm conditions around the snow. High levels of precipitation add to the risk for melting because if rain is coming down instead of snow, due to weather conditions above freezing temperature, the water coming down on previously deposited snow will melt the snow causing the snow deposits to deplete.

In Figure 2 there is a map of Idaho, part of Wyoming, Washington, and Oregon that displays the different snow classifications for the areas contained on the map. Focusing on Oregon specifically it can be seen along the Cascade Range most of the snow is considered to be in the “at-risk” classification. This snow is susceptible to melting due to the climate conditions, even small fluctuations can cause a change in the snow pack and total reservoir storage.



Conclusion

In conclusion while there is a clear threat to the water resources contained within the snowpack there is no clear monitoring or conscious effort to the protection of these environments. While we have a monitoring system in place that currently keeps track of the water flow and stream flow throughout the mountainous hydrologic cycle it does not account for climate change and that processes impact on the snow environment. The amount of potential damage to multiple facets of life resulting from climate change in the snowy regions is vast. Impacts not only include the normal weather we would see but also could affect the area economically, how long we see winters for, and could completely wipe out some lower elevation ski areas. The Envision model is a good start to begin looking at the impacts and possible fluctuations that all factors of mountain hydrology must account for. However there is still much left to be desired as the monitoring systems do not allow for the most accurate judge of the statistics needed to form accurate hypotheses and proper adaptations/interventions if necessary.

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Perspectives on Climate Change, Mountain Hydrology, and Water Resources in the Oregon Cascades, USA

Anne W. Nolin
nolina@geo.oregonstate.edu
Department of Geosciences, Oregon State University, Corvallis, OR 97331, USA

From both social and environmental perspectives, water is the main connection between highland and lowland processes in mountain watersheds: Water flows downhill while human impacts flow uphill. For example, in the Oregon Cascades mountain range, geology, vegetation, and climate influence the hydrologic connections within watersheds. Geology determines which watersheds are surface runoff-dominated and which are groundwater-dominated. In this Mediterranean climate with dry summers, surface runoff watersheds will consistently experience near-zero late summer discharge, so declining snowpacks will have little effect on low flows. This contrasts with groundwater-dominated watersheds, where a shift from snow to rain or a decline in precipitation will reduce recharge, thereby reducing late summer groundwater contributions to streamflow. Earlier snowmelt causes forests to transpire earlier, resulting in decreased springtime streamflow. Reduced snowpacks lead to soil moisture stress, making forests more vulnerable to extensive wildfires and affecting the lifespan and composition of forests. Monitoring and quantifying these complex linkages and feedbacks require appropriate measurement networks. Sampling strategies often use watershed typology to identify where measurements should be focused. Such an approach should include not only established watershed classification parameters such as topology and geology but also interannual climate variability and land cover. As concerns of water scarcity and vulnerability move to the forefront, our watershed classifications should be extended to include ecosystem and social–ecological parameters. An integrated and agent-based modeling scheme called Envision has been developed to simulate alternative future landscapes at the watershed scale. Using fully coupled models of hydrology, ecosystems, and socioeconomics, decision-makers can simulate the effects of policy decisions in conjunction with other climate forcing, land use change, and economic disturbances. To understand the combined impacts of climate change and humans on water in mountain watersheds, researchers must develop integrated monitoring and modeling systems that explicitly include connections across eco-hydrologic and social-ecological systems.

Keywords: *Mountain hydrology; water scarcity; vulnerability; snow; climate change; watershed classification; eco-hydrology; social–ecological system; agent-based modeling; USA.*

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Introduction

Mountains are a source of high-quality water and critical water storage (Viviroli et al 2007; Viviroli et al 2011), rich biodiversity, hydropower, food, and building materials (Ives et al 1997; Blyth et al 2002; Beniston 2003). Water, as the fundamental linkage across the biosphere and as the essential resource for human society, is the ubiquitous connection for virtually all aspects of the mountain social–environmental system.

Mountain systems worldwide have been the subject of recent attention with regard to vulnerability to climate change impacts. Within this context of climate change, vulnerability has been described as "the degree to which [geophysical, biological, and socioeconomic] systems are susceptible to, and unable to cope with, adverse impacts" (Schneider et al 2007). More broadly, Adger (2006) defines vulnerability as "the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt." However, vulnerability to climate change is relative and should be viewed in terms of the specific nature of the entity (eg a mountain watershed, a community) and the particular climate change stressor(s) (eg increased winter temperature, declining snowpacks) and have specific means for evaluating the resulting complex interactions between the entity and the climate change stressor(s) (Ionescu et al 2009). The concept of dynamic vulnerability, in which linkages and feedbacks between biophysical and socioeconomic stressors produce nonlinear vulnerability responses (Westerhoff and Smit 2009), is particularly relevant to mountain watersheds with their strong gradients of climate, hydrology, and ecosystems and human interactions.

This paper presents examples of climate-induced vulnerability to water scarcity in the Oregon Cascades mountain range. It is perhaps surprising to investigate water scarcity in what is typically considered a water-rich region. However, complex interactions of climate, geology, vegetation, and humans create circumstances of

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Projected climate change impacts on forest land cover and land use over the Willamette River Basin, Oregon, USA

Nick Barrera, Earth and Physical Sciences Department, Western Oregon University, Monmouth, Oregon, 97361
email: nbarrera15@wou.edu

Abstract

Over time the way we use land largely may remain the same. However, when taking into consideration of how the world is changing on a daily basis, we must see that not everything in this world is immune to change. While climate change goes on around us, the change lies in vegetation in some places and water in others but overall it will effect everything eventually.

All of the things climate change does to the environment could change the pattern in which things will grow or even eliminate ecosystems. This does not go without saying the potential for human involvement. As humans help the process of changing the environment, we may be changing the way vegetation and animals live.

Introduction

All of the trees in the Willamette river basin (WRB) are changing over time. When the environment undergoes the same changes that is brought on by climate change is effecting the water and plant life in the river basin. Climate change is making a large impact on the world, and considering the environment of the river basin, there are plenty of things that can be changed or even destroyed.

When the environment is going through the water cycle and the water starts to run out, it makes the water cycle stop working. While the cycle is running its course, the lack of water leads to a drought. All changes will not only effect water but it will effect the plant life as well. This includes the changing of the species of plants that live there.

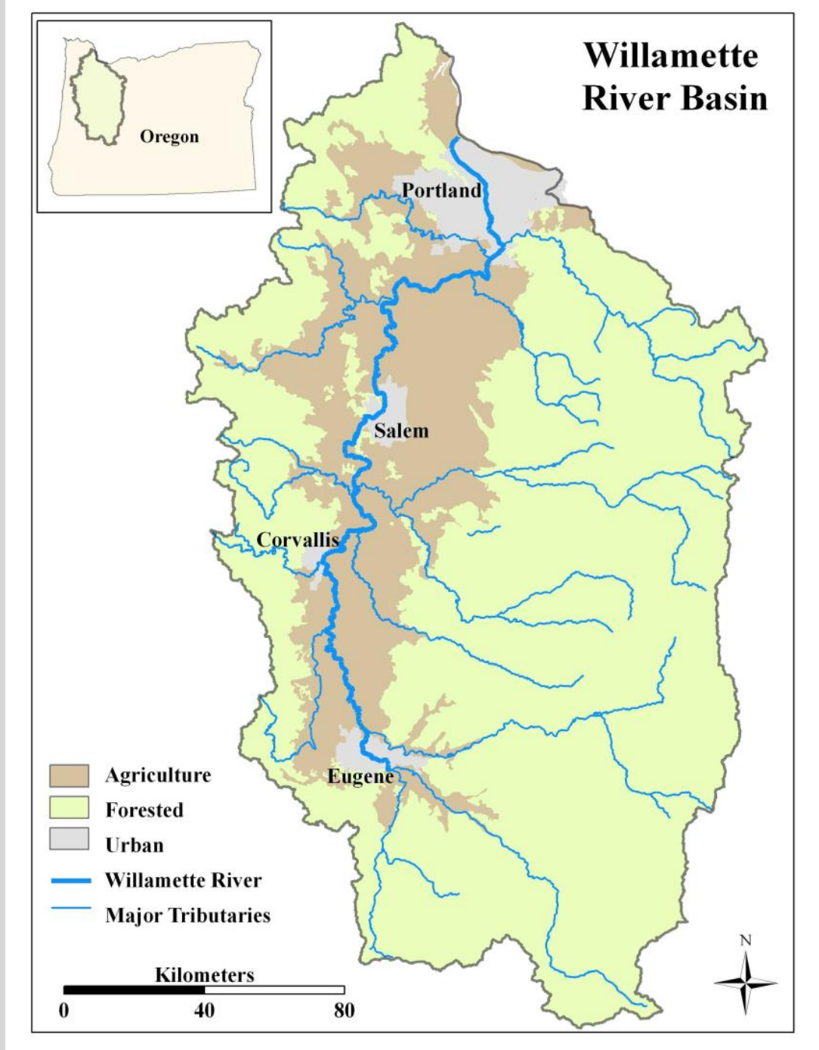
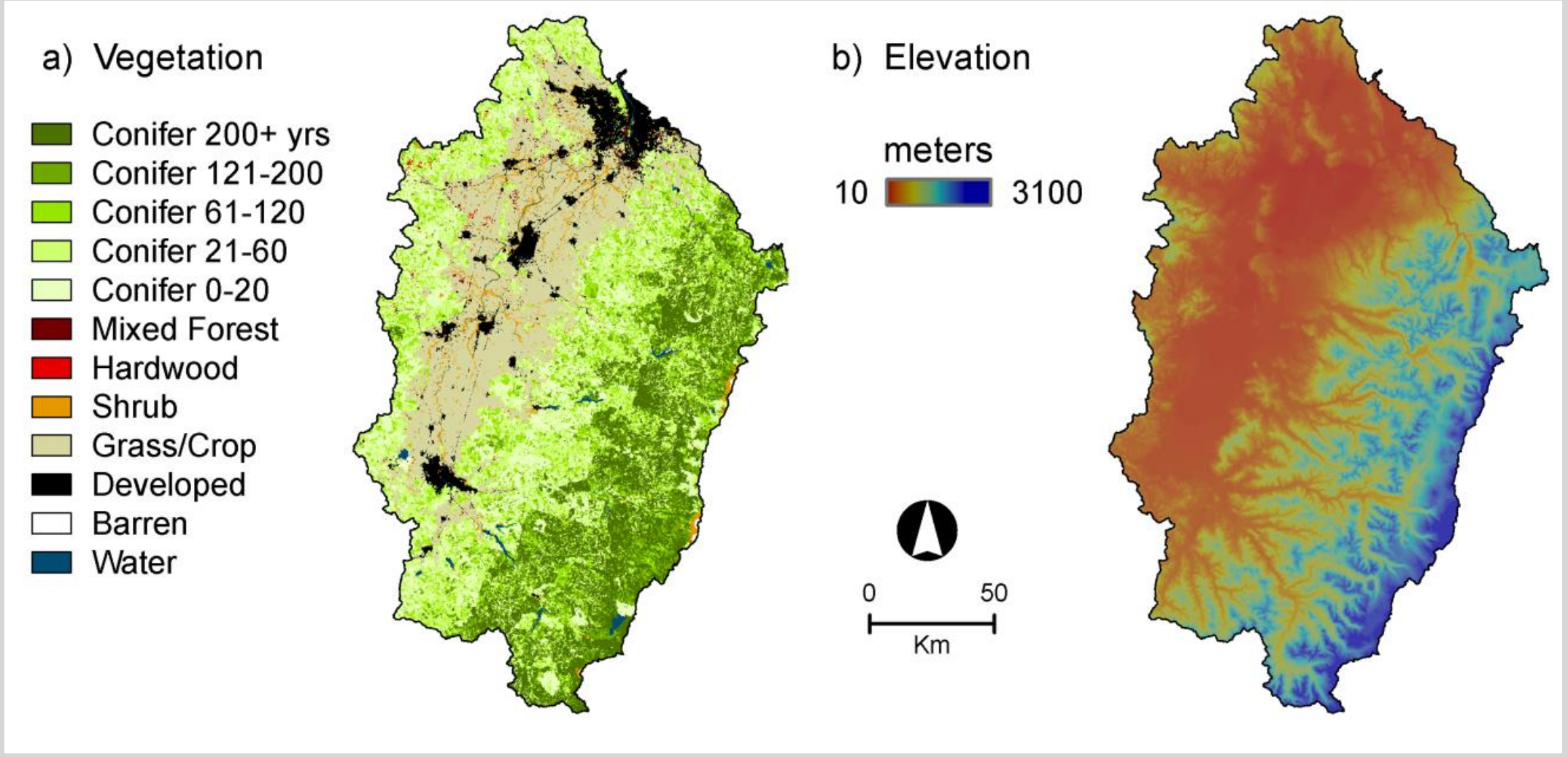


Figure 1. Location map, vegetation and land-use of Willamette Basin.



Flora Changes

Over time, the plant life in the WRB has changed greatly; it has taken time but due to increasing climate change the trees in the basin have not only gone through man made damages but also climatic changes. Fires are large cause for change in many different forested ecosystems, due to the burning of forests the trees are put under private and public lands. While these trees are in risk of future fires, they are also at risk of the change in species.

The trees are at major risk during the climate change events, during the change in temperature it brings a change in species. While the basin was a majority of needle leafed trees, it has begun a shift in this trend. As the area heats up, these needle leafed trees are starting to disappear due to the rising temperature of the river basin. In a study performed by David Turner, he and his crew ran tests to see what the WRB would look like in ninety years. The results came back with a lack of alpine and conifer forests, showing that the increase of temperature will eventually wipe out certain types of trees and make it a subtropical climate (Turner, et al. 2015).

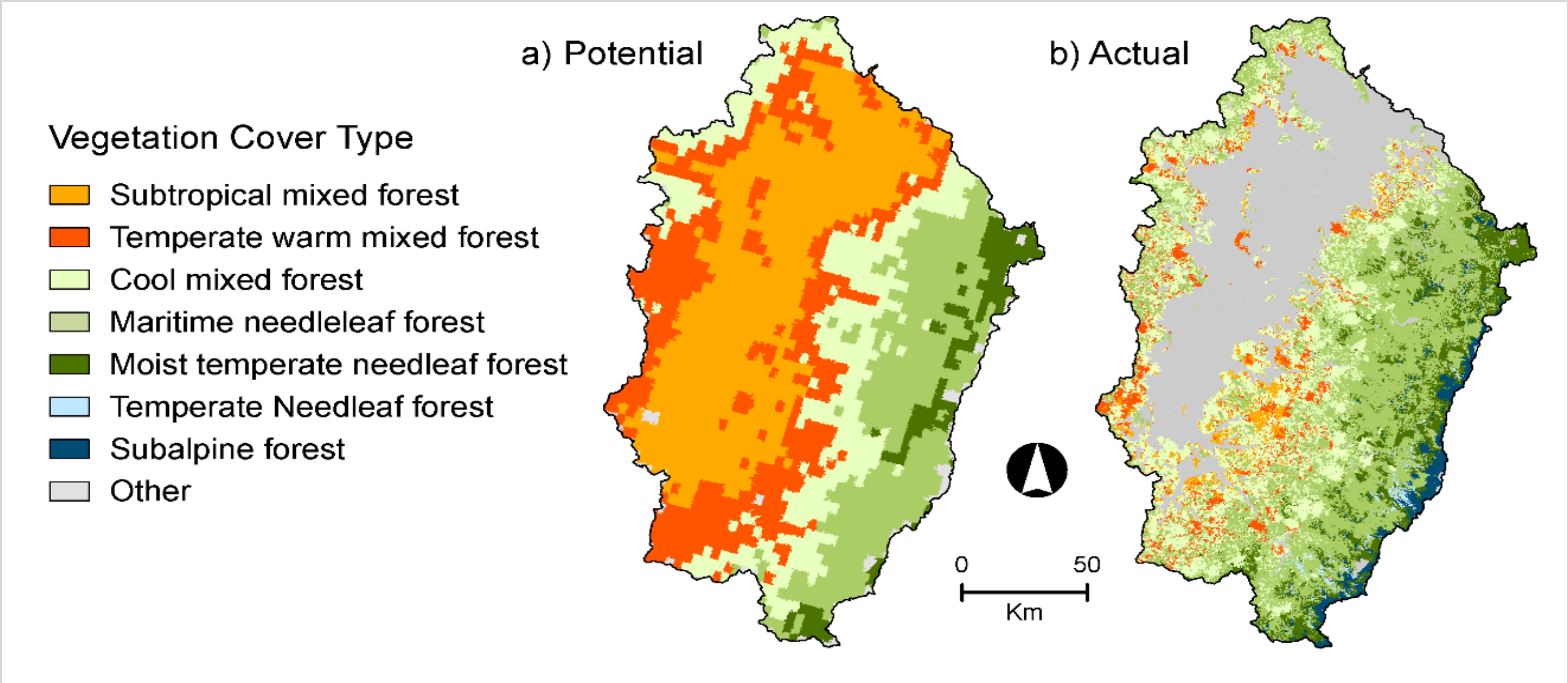


Figure 2. Predicted vegetation changes in the Willamette Basin.

Drought Risks

Along with the change in trees, the water is going to be effected greatly in the way the climate is going. This will result in extremely negative ecosystem changes. The water cycle is going to be changed as the basin heats up, the increase in temperature results in a major reduction of the water and an increase in the dry season. Many of the factors that may indicate droughts might not actually mean there will be a drought in the area. One of the main issues that causes this problem with the water cycle is climate change. Heating of the climate around the water basin means that due to the way the climate works in the area, the wet season does not go year round, beginning in October and ending in May (Franczyk and Chang 2009a, b). Due to the short amount of time the basin gets rain, it leaves the area susceptible to drought.

The storage sources of the basin are the watershed and the snow build ups. When the water is stored in the snow and ice, it gradually melts over the spring leading into the summer, this water seeps into the watershed and makes it so this water will last. When it is considered how deep the watershed is, this water can last for a long time. Climate change makes the process go faster than the basin can handle, snow melts faster than it can replenish. The warming of the air and climate is being caused also in part by the effect of orographic lifting, mountain snow and run off will make its way down quicker than in other areas.

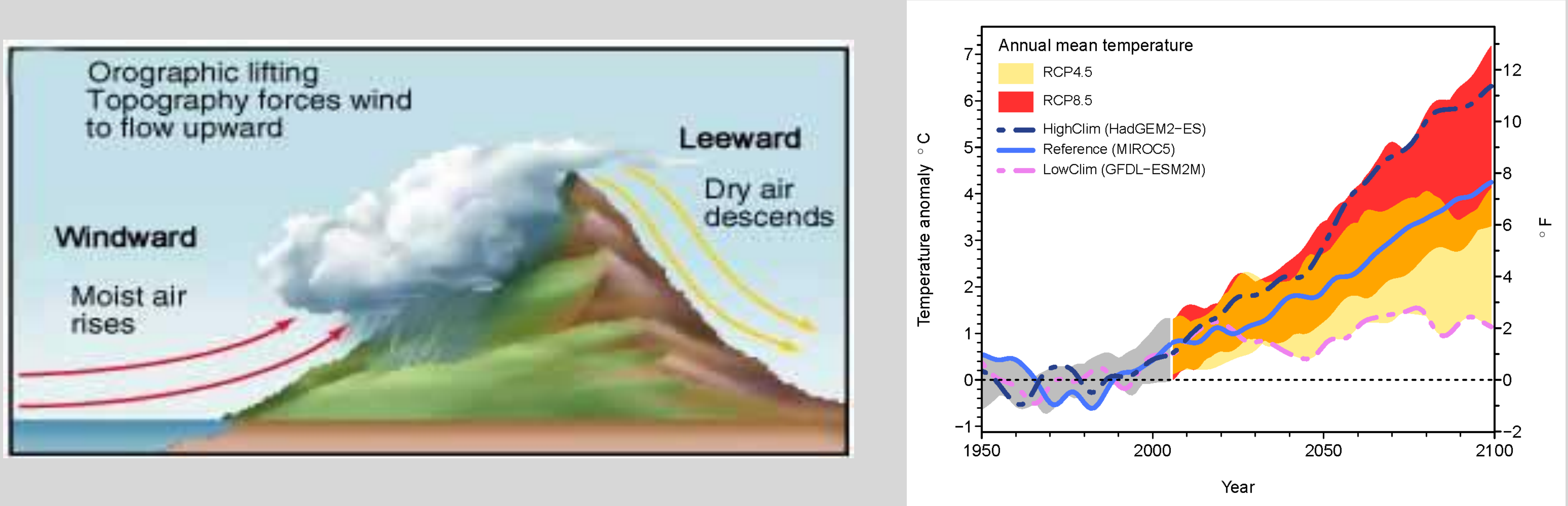


Figure 3. Predicted climate trends in the Willamette Basin.

Conclusion

Climate change is already a big issue in today's society, and when this is causing damage to major water basins, something must be done to prevent this. The warming of the earth is making the snow melt quicker, making the water evaporate quicker and causing the water to cycle faster.

Trees are changing and making it so not only the climate changes but the whole biome is changing as well. Currently a temperate mixed forest, this will change greatly over time. As the world heats up, the temperate climate in the Willamette River Basin will turn to Subtropical over the next ninety years from 2010 to 2100. This can be seen as a big issue, showing that the change in climate will be severe and cause damages not only to the flora of the basin but the fauna. Humans are a part of this fauna and we are also helping cause this climate change, there is no stopping this change at this point, but we can do plenty to slow this change.

We may not be able to reverse the effects of climate change but we can do other things. Using energy efficient appliances or even using less electricity could change the trend in climate change. The way humans are doing things now will only continue to increase the effects of climate change. However, if we use electricity and power and other damaging things more efficiently, we could even out the trend and make it less damaging. This issue is a potential disaster but there are ways to slow it, and if we cannot, a lot of biomes and animal species will be damaged or even eliminated altogether.

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Projected climate change impacts on forest land cover and land use over the Willamette River Basin, Oregon, USA

David P. Turner[1] · David R. Conklin[2] · John P. Bolte[3]

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Abstract Upland forests in the Pacific Northwest currently provide a host of ecosystem services. However, the regional climate is expected to warm significantly over the course of the 21st century and this factor must be accounted for in planning efforts to maintain those services. Here we couple a dynamic global vegetation model (MC2) with a landscape simulation model (Envision) to evaluate potential impacts of climate change on the vegetation cover and the disturbance regime in the Willamette River Basin, Oregon. Three CMIP5 climate model scenarios, downscaled to a 4 km spatial resolution, were employed. In our simulations, the dominant potential vegetation cover type remained forest throughout the basin, but forest type transitioned from primarily evergreen needleleaf to a mixture of broadleaf and needleleaf growth forms adapted to a warmer climate. By 2100, there was a difference (i.e., climate/vegetation disequilibrium) between potential and actual forest type for 20–50 % of the forested area. In the moderate to high climate change scenarios, the average area burned per year increased three to nine fold from the present day. Forest harvest on private land is projected to be affected late in the century because of fire altering the availability of rotation-age stands. A generally more disturbed and open forest landscape is expected, which may significantly alter the hydrologic cycle.

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✉ David P. Turner
david.turner@oregonstate.edu

[1] Forest Ecosystems and Society, College of Forestry, Oregon State University, Corvallis, OR 97331-7501, USA

[2] Common Futures LLC, Corvallis, OR, USA

[3] Biological and Ecological Engineering, Oregon State University, Corvallis, OR, USA

Western Oregon
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Earth Science

Analysis of precipitation extremes: Assessment of regional climate models over the Willamette River Basin

Tunya Dhevaphalin, Earth and Physical Sciences Department, Western Oregon University, Monmouth, Oregon, 97361
email: Vdhevaphalin14@wou.edu

Abstract

An appropriate, rapid and effective response to extreme precipitation and any potential flood disaster is essential. Providing an accurate estimate of future changes to such extreme events due to climate change are crucial for responsible decision making in flood risk management given the predictive uncertainties. In the work of Halmstad, et. al. (2012) they provided a comparison of dynamically downscaled climate models simulations from multiple models including 12 different combinations of General Circulation Model (GCM) – regional climate model (RCM), which offers an abundance of additional data sets. The three major aspects of this study include the bias correction of RCM scenarios, the application of a newly developed performance metric and the extreme value analysis of future precipitation. The dynamically downscaled data sets reveal a positive overall bias that is removed through quantile mapping bias correction method. The added value index calculated to evaluate the models' simulations. Results from this metric reveal that not all of the RCMs outperform their host GCMs in term of correlation skill. Extreme value theory was applied to both historic, 1980-1988, and the future, 2038-2069, daily data sets to provide estimates of changes to 2- and 25- year return level precipitation events.

Introduction

The Willamette River basin has topographical variability and tendency for significant precipitation. The extreme value analysis results showed significant difference between model runs for both historical and future periods with considerable spatial variability in precipitation extremes. Among the potentially significant impact of future climate change, the spatial and temporal variation of precipitation extremes, in terms of intensity and frequency, is of great importance to water resources engineers and decision makers in regards to events of floods and droughts. The process of downscaling outputs from GCMs has been established as the primary approach for addressing the inadequacies of large scale resolution models. There are two main classes of downscaling procedures: statistical and dynamical. Statistical approaches involve determining reliable statistical relationships between large scale climate variables that are well represented by GCMs, such as pressure fields and low scale variables such as temperature or precipitation. Dynamic downscaling approaches are based on the same numerical integration of differential equations, as in GCMs, but over a smaller spatial and temporal domain.

Study Area

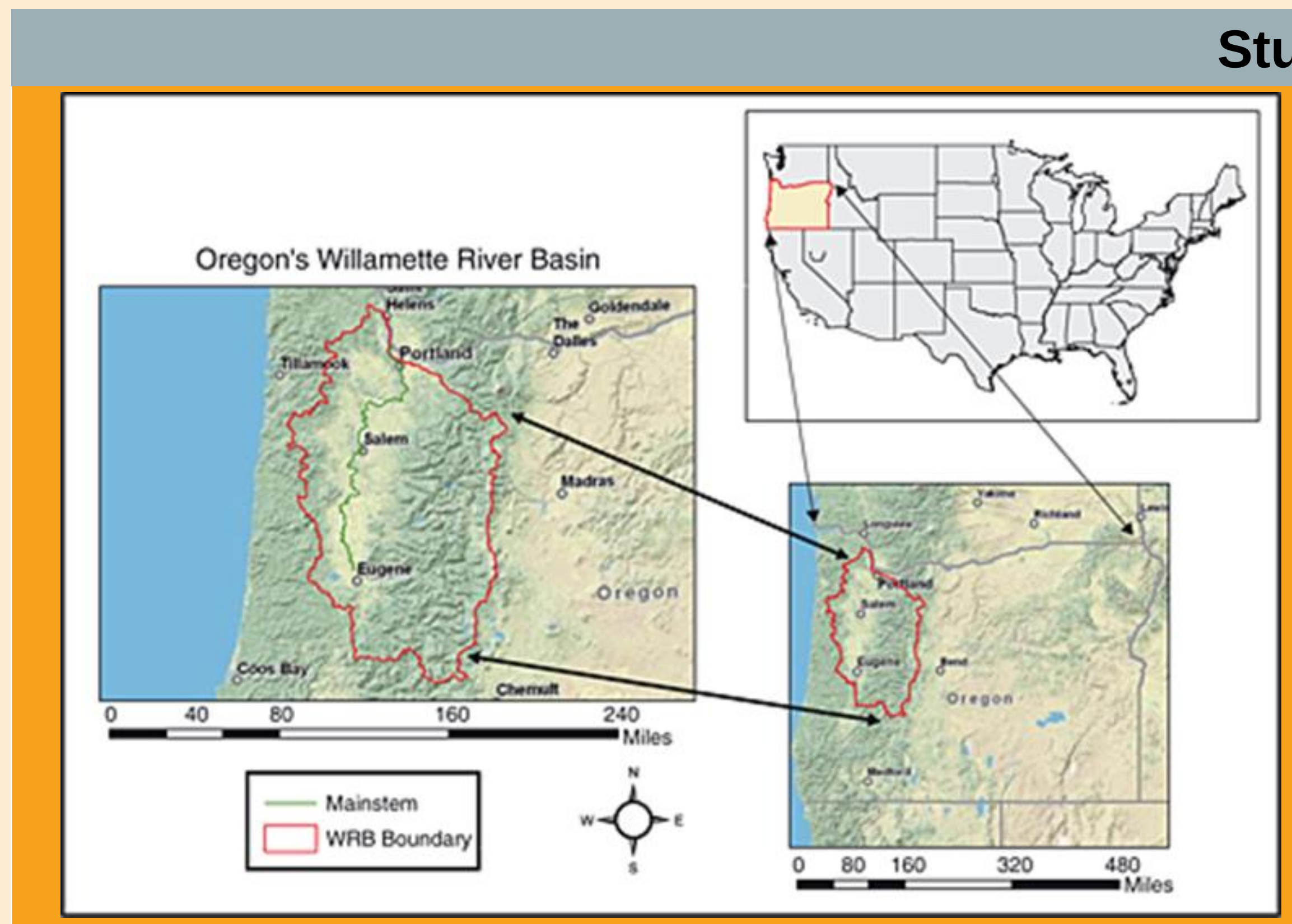

Figure 1 the study area in the Willamette River Basin.

The Willamette River Basin in Oregon (figure 1) is the 13th largest river in the United States, and captures a considerable amount of runoff. It covers a drainage area of 29,728 squared kilometer. Oregon has temperate marine climate with cool wet, with 80% of annual precipitation, and warmer mostly dry summers. Precipitation and rainfall annually can reach from 40 inches in low elevation areas, up to 175 inches in high elevation areas. There has been studies using LiDAR and GCM data that investigates the potential change to floodplain and flood magnitude in sub basins of the Willamette River Basin.

Data

Precipitation rate data [kgm-2 s -1], at a temporal resolution of 3 h, was obtained over both a historical period 1979–2004 as well as a future period 2038–2069. The spatial location of each RCM's grid points within the WRB is displayed in Figure 2. The number and location of grid points within the WRB varies between RCMs, owing to inherent design differences of each model. The spatial location of each RCM's grid points within the WRB is displayed in Figure 2. The number and location of grid points within the WRB varies between RCMs, owing to inherent design differences of each model. To provide a comparison with observed precipitation over the WRB, gridded data set was used. This data set covers the period 1950–2000 and provides surface level information regarding numerous climatic variables at three hourly time intervals. The data set provides values of total daily precipitation over the continental USA obtained from the stations of the National Oceanic and Atmospheric Administration's Cooperative Observer. The precipitation data over the WRB used in this study was obtained at 1/8th degree resolution and served as an observational benchmark upon which dynamically downscaled data sets were compared.

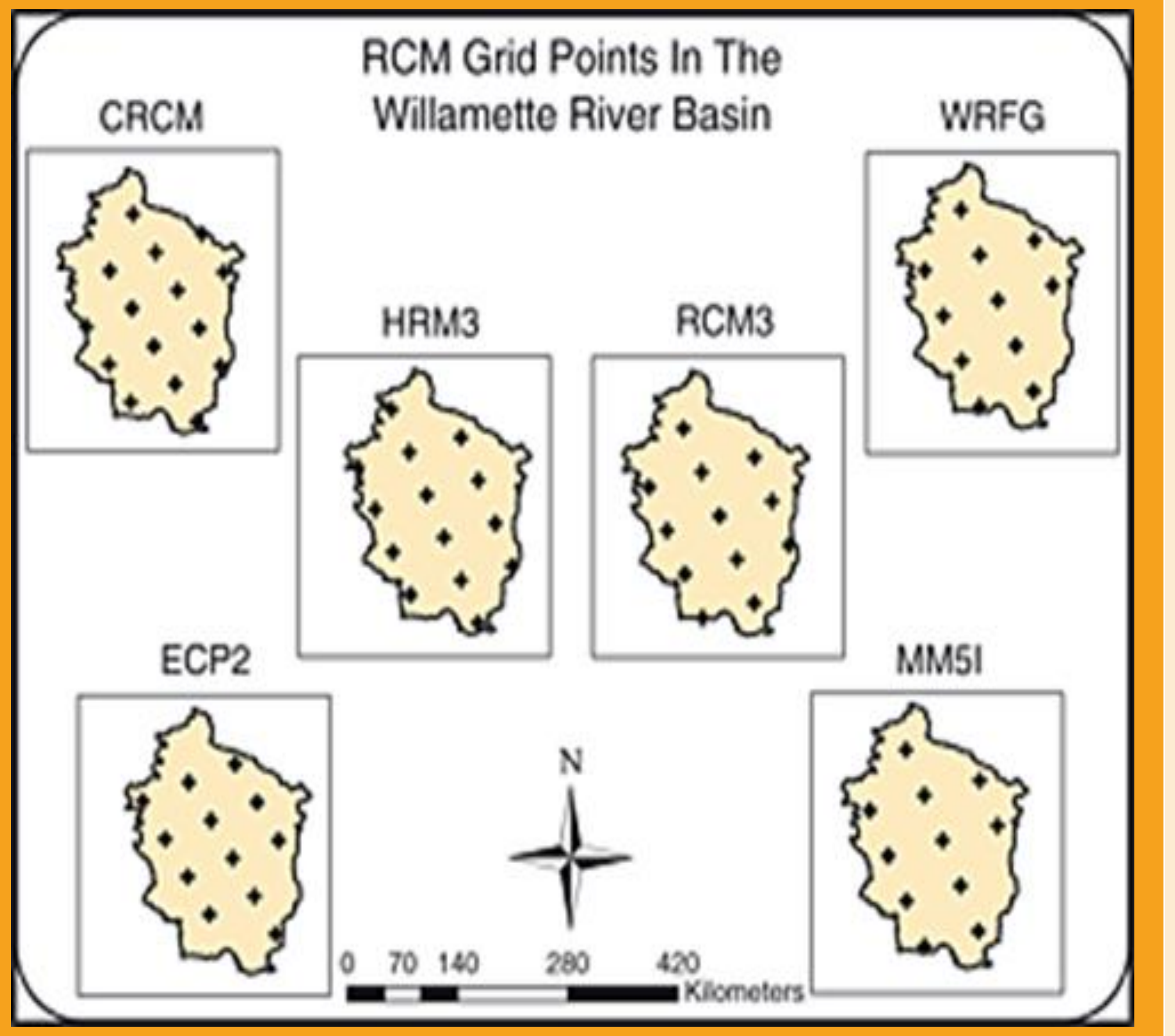

Figure 2 Regional climate model grid points in the Willamette River Basin.

Methodology

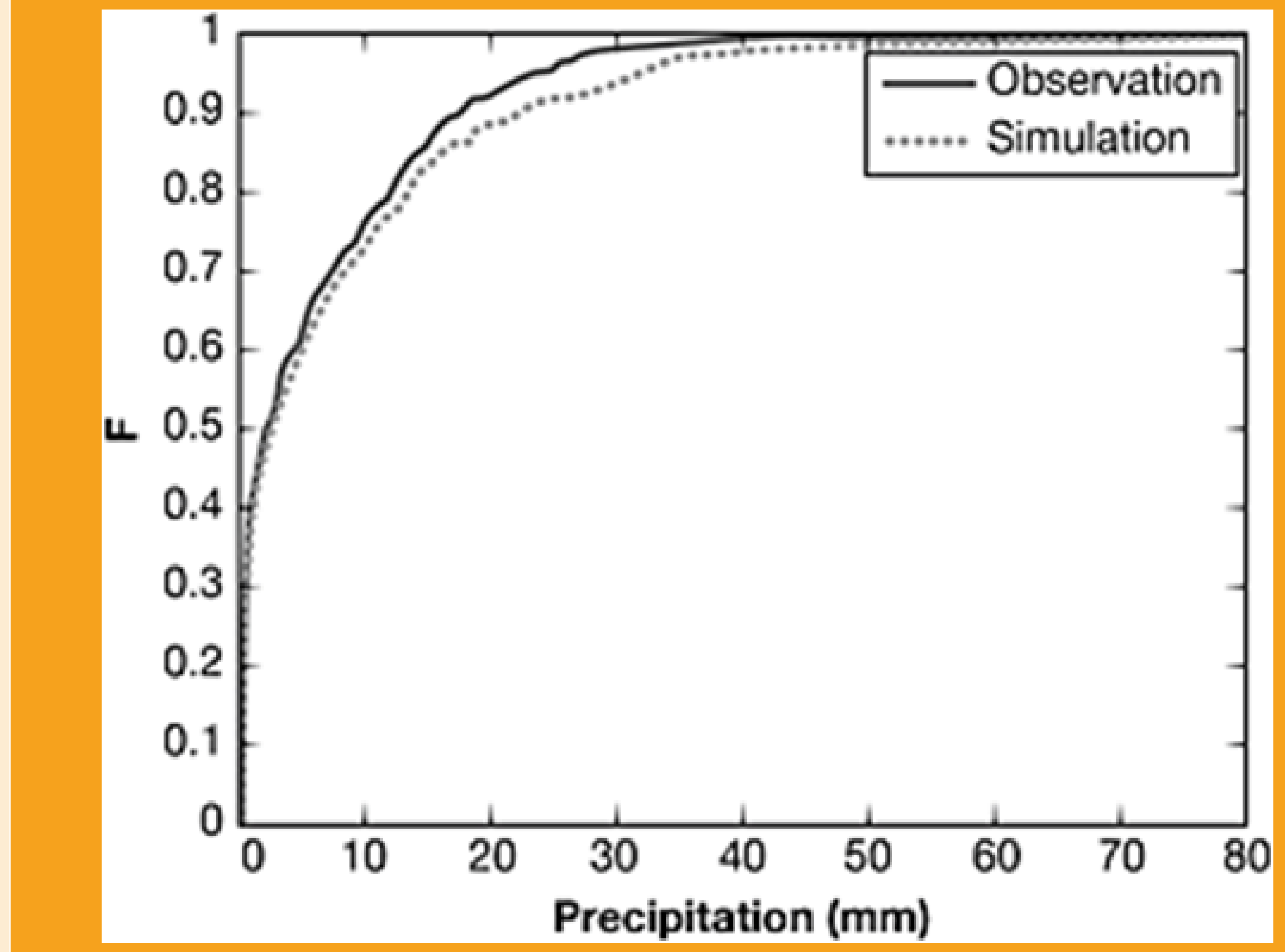

Figure 3 Mapping of the cumulative distribution function.

For this study, the quantile mapping approach was implemented. In this procedure of bias correction, the observed and simulated data sets are each characterized in terms of their full distribution of daily values for each month because it does not rely on adjusting the mean, standard deviation or other standard statistical parameters. A scaling factor is developed between the observed and the simulated data sets over a historic period. For both the observed and the simulated data sets, the cumulative distribution functions (CDFs) are computed on a monthly basis. Figure 3 shows the CDF. After computing the CDFs, the scaling factor determined based on the respective quantile values during the observed period are then applied for the projected (future) period.

Results

Results of the quantile mapping bias correction technique are displayed in Figure 4 . Mean monthly precipitation values for January and August over the historical period, 1980–1998. The bias is stronger in the month of January because of the higher magnitude of precipitation during the month, whereas August, a relatively dry month over the WRB, reveals a smaller magnitude in the bias. During the month of January, the simulation tends to over predict precipitation in the WRB. This positive bias is an attribute that has been documented before in dynamically downscaled data sets. The bias present in the simulation data set during the month of August is also slightly positive, demonstrated by the range of bias values present before bias correction. The bias correction procedure effectively corrects for this positive bias.

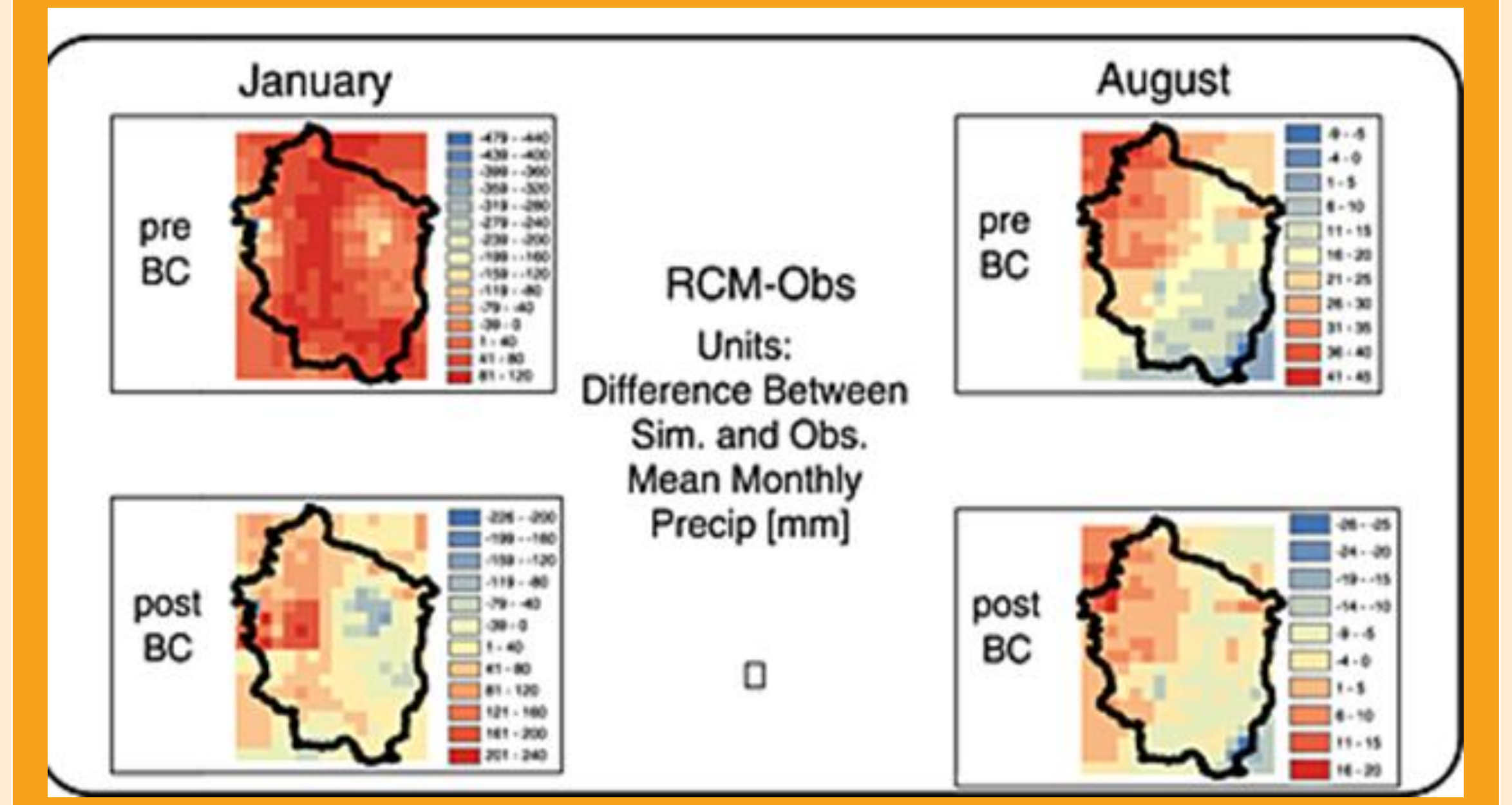

Figure 4. Results of quantile mapping bias correction.

Conclusion

The results of this study demonstrate two key facts regarding the use of downscaled climate data sets. First, applying a bias correction scheme to any downscaled data set is a needed and important step yielding more accurate results. The quantile mapping procedure was implemented and successfully reduced the difference between observed and simulated precipitation over the WRB by correcting for the positive bias that is present in RCM data sets and reducing overall bias magnitude. Implementing fundamentals to climate data sets provides estimates of changes to variable values, such as precipitation, because of climate change. Using the GPD distribution, this study obtained estimates of changes to 2- and 25-year extreme precipitation event magnitudes over the WRB. The results indicate that these return level magnitudes will increase in the future period 2038–2069 compared with simulations over the historical period 1980–1998.

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HYDROLOGICAL PROCESSES
Hydrol. Process. **27**, 2579–2590 (2013)

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Analysis of precipitation extremes with the assessment of regional climate models over the Willamette River Basin, USA

Andrew Halmstad, Mohammad Reza Najafi and Hamid Moradkhani*
Department of Civil and Environmental Engineering, Portland State University, Portland, OR, USA

Abstract:

An appropriate, rapid and effective response to extreme precipitation and any potential flood disaster is essential. Providing an accurate estimate of future changes to such extreme events due to climate change are crucial for responsible decision making in flood risk management given the predictive uncertainties. The objective of this article is to provide a comparison of dynamically downscaled climate models simulations from multiple model including 12 different combinations of General Circulation Model (GCM)–regional climate model (RCM), which offers an abundance of additional data sets. The three major aspects of this study include the bias correction of RCM scenarios, the application of a newly developed performance metric and the extreme value analysis of future precipitation. The dynamically downscaled data sets reveal a positive overall bias that is removed through quantile mapping bias correction method. The added value index was calculated to evaluate the models' simulations. Results from this metric reveal that not all of the RCMs outperform their host GCMs in terms of correlation skill. Extreme value theory was applied to both historic, 1980–1998, and future, 2038–2069, daily data sets to provide estimates of changes to 2- and 25-year return level precipitation events. The generalized Pareto distribution was used for this purpose. The Willamette River basin was selected as the study region for analysis because of its topographical variability and tendency for significant precipitation. The extreme value analysis results showed significant differences between model runs for both historical and future periods with considerable spatial variability in precipitation extremes. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS precipitation extreme; climate change; dynamic downscaling; bias correction; NARCCAP

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INTRODUCTION

Among the potentially significant impacts of future climate change, the spatial and temporal variation of precipitation extremes, in terms of intensity and frequency, is of paramount importance to water resources engineers and decision makers. The primary approach for evaluating potential changes to hydroclimatic variables is through the use of climate models that simulate aspects of the global climate cycle. During the last three decades, the number and complexity of climate models have increased substantially, more physical processes are simulated and the coupling between individual sea, atmosphere and land-based processes has been improved (Xue *et al.*, 2001; Wang *et al.*, 2004; Diffenbaugh *et al.*, 2005; Mearns, 2007; Solomon, 2007; Mearns *et al.*, 2011; Yuan and Liang, 2011). Recent advancements in modelling spatial and temporal climate variables at finer scales allow for regional impact analysis studies. The ability to investigate the impact of climatic change at a regional scale has the potential to inform water resource managers and decision makers regarding the changes in the climate cycle that will influence extreme events, that is, floods and droughts. To provide valuable information regarding potential climatic changes, the results from multiple climate model simulations can be investigated and compared with reduce the overreliance on one model and quantify model uncertainty.

During the last two decades, numerous improvements in the field of climate change research have bolstered confidence in the predictive capability of climate models. Through increased international research efforts made possible by initiatives such as multimodel ensemble investigation projects (described in greater detail in the section on Multimodel Ensemble Projections), climate models have undergone extensive analysis by an increasing number of investigators at virtually all levels of research (Solomon, 2007). All major component phases (atmospheric, oceanic and terrestrial) have seen improvement in terms of model formulation (improved transport and dynamics schemes), increased resolution (vertical, horizontal and temporal) and represented processes (such as direct and indirect aerosol effects) as well as many other aspects (Solomon, 2007). Most notably for this study, the overall distribution of precipitation and the capability of models to simulate extreme events are noted by the Intergovernmental Panel on Climate Change-Fourth Assessment Report (IPCC-AR4) as areas, which have seen improvement.

Within the climate modelling community, it has long been speculated that increasing the resolution of climate models is necessary to improve the estimates of regional-scale phenomena, such as precipitation (e.g. Giorgi, 1990; McGregor, 1997; Murphy, 1999; Caldwell, 2010; Di Luca *et al.*, 2011;). The process of downscaling outputs from GCMs has been established as the primary approach

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*Correspondence to: Hamid Moradkhani, Department of Civil and Environmental Engineering, Portland State University, Portland, OR, USA. E-mail: hamidm@cecs.pdx.edu

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Vulnerability of Water Supply and Climate Change in the Oregon Cascades

Scott Warren, Earth and Physical Sciences Department, Western Oregon University, Monmouth, Oregon, 97361
email: swarren11@mail.wou.edu

Abstract

Understanding the effects of climate change on various environments is challenging at best, especially the Columbia and McKenzie rivers which rely on snow melt for flow. The rivers are relied on heavily for fresh water resources and play a pivotal role in the marine ecosystem. The average warming for the 20th century is **+0.82 C**. Models show an increase of **+0.5 to 2.5 C** increase by 2020's and **+1.5-3.2 C** increase by 2040. Effects on stream flow are expected to include reduced snowpack from snow falling as rain and from an earlier melting season. Consequences for forests may include migration of tree species, invasion of other species, water competition from lack of groundwater recharge. Ecological effects are not understood, but marine environments will face more challenges. Reduced stream flow and temperature increases, urbanization and stream modification threatens salmon activity and habitat.

A clear picture is difficult as data is lacking in regards to salmonids in their open sea environment. Current trends could possibly push the Salmon further north out of the Northwest. Additionally, Competing business interests create another array of policies, politics, and administrative issues. Many business own overlapping geographic sections along the Columbia and McKenzie rivers. Resource managers are reluctant to use new data as it is not in the "scope" of their interest, yet many acknowledge climate change. The need to recognize sensitivity, plan, create policies are paramount to adaptability.

Introduction

The Pacific Northwest is showing evidence that the region is undergoing a warm phase from the Pacific Decal Oscillation (PDO) and from CO2 emissions, most notably anthropogenic. Understanding of climate change has substantially improved in last few decades. The question of how climate change will affect natural resources is not understood and is lacking in research. The intent of this study is to understand current stresses to predict future stresses in order to help mitigate effects. Oregon is home to both the Columbia and McKenzie rivers driven by snowmelt. An area of industrialization, residence, recreation, and ecological habitat. Plans lacking in planning to deal with the consequences of global warming on such a vital resource.

Figure 1. Photo of Bonneville Dam on the Columbia River. This image shows both industrialization, modification of stream flow, and residences. Photo by US Army Corps of Engineers via Wikipedia

Climate Trends

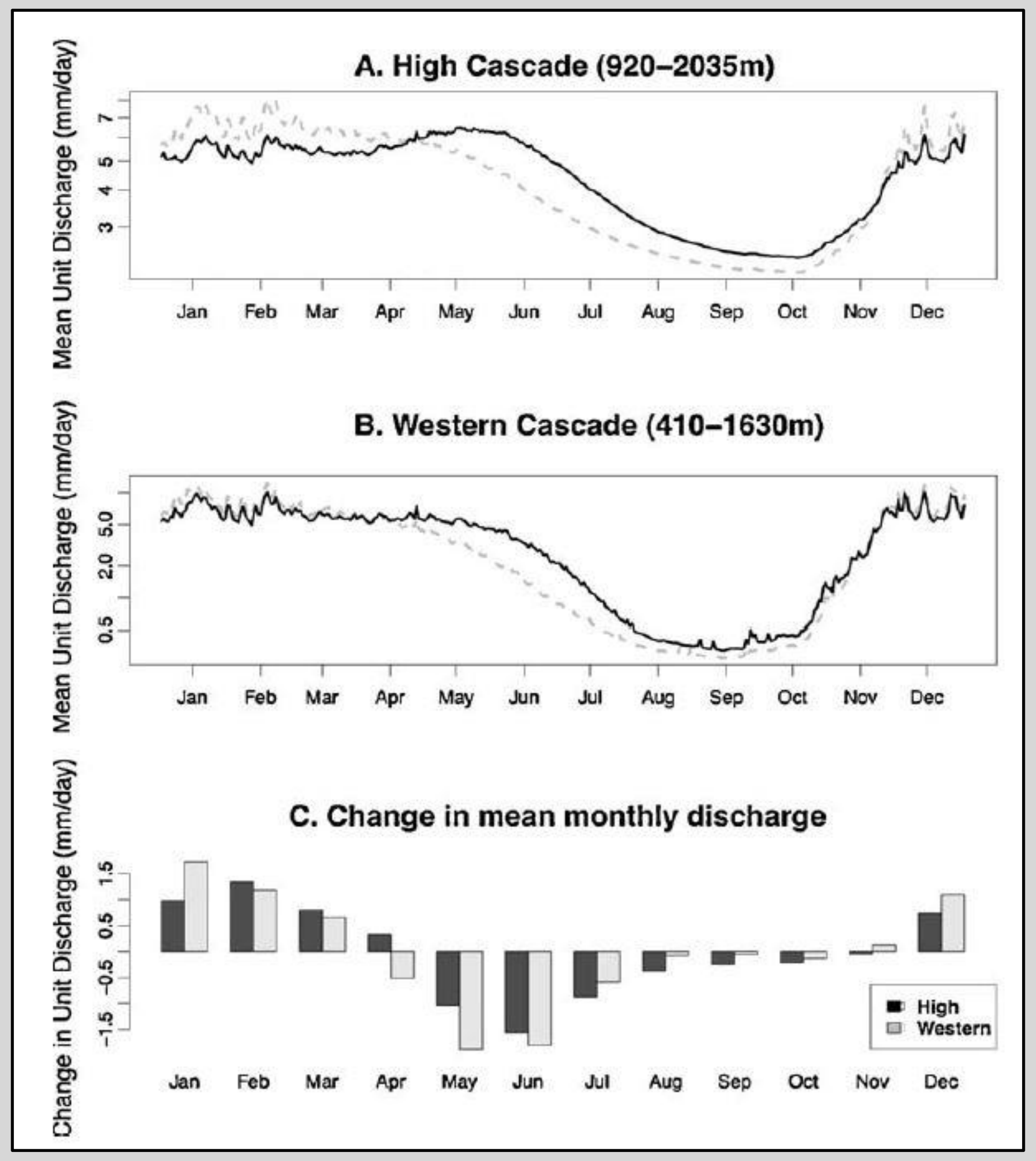

Figure 2. Projected effects of a 1.5 C uniform temperature increase in the A.) High Cascades, B.) Western Cascades, and C.) Change in mean monthly discharge (Farley, K.A., et. Al 2010)

Observed average climate warming during the 20th century was +0.82 C. The Pacific Northwest has experienced 6 multi-year droughts since 1900. 5 of which occurred during warm phases of PDO. Using new collected data, 20th century warming rates and model predictions were projected into the 2020's and 2040's. By the 2020's, the Pacific Northwest will be facing temperature increase of +0.5-2.5 C and +1.5-3.2 C by 2040's. Many resources are affected by climate change, water being most affected. Rivers such as the Columbia and McKenzie are snowmelt driven rivers and show greatest change when dealing with freshwater resources.

Smaller streams tend to become flooded and inundated with rainfall, thus not producing an accurate insight into streamflow and snowpack. Warming seems to be associated with the warm phase of the Pacific Decadal Oscillation (PDO) which have an average of 20-30 year life span. Warm phases of El Nino/South Decadal have be implicated in causing warming, but in a much shorter time frame. Ultimate effects will be demonstrated by increased streamflow in the winter season because increasing quantities of snow falling as rain. Lack of snow reduces the amount of water in storage as snowpack. Coupled with an earlier melting season, streamflow is reduced in the summer causing strain on the resources and others that depend on it.

Climate Change and Environment

Climate change can have a heavy influence on our regional environment in the Pacific Northwest. Forests are likely to experience effects of climate change. Reduction in snow pack and groundwater recharge creates competition for water, invasion of species, migration of species, and health. Plants are most vulnerable during their seedling and young phases. Resulting stress will likely influence tree lines. Plants that require more water may move up in elevation where water is more plentiful. This can lead to further reduction in streamflow from snowpack. Already stressed plants and trees may succumb to illness, parasites, insect infestations, or have poor fire resistance. An increase in forest fires and their severity will destroy forests to the point where re-establishment takes much longer. Human fire and forest intervention has allowed tinder to accumulate to a level causing fires to burn longer and hotter.

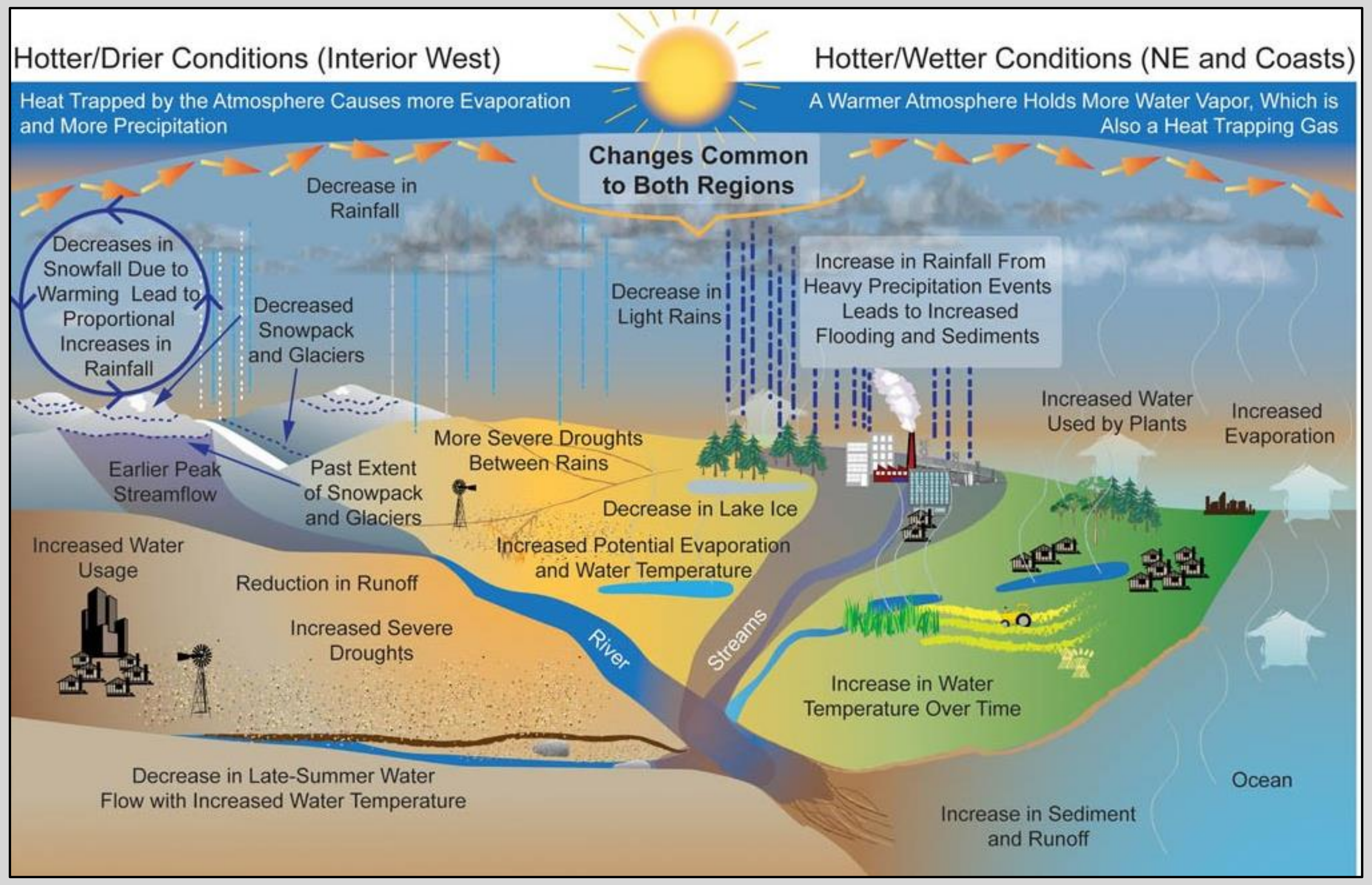

Figure 3. Diagram showing the over all hydrologic cycle and effects of climate change due to increasing temperatures emissions, mainly CO2 and Sulfate Aerosols. Diagram created by Environmental Protection Agency (EPA)

Marine environments, specifically salmonids are at risk. Salmon already face environmental challenges from urbanization, dams, competing stock from hatcheries, and etc. Salmon have a low thermal gradient and rising stream temperatures could pose risks. Migration patterns of salmon to and from the ocean is not fully understood. There is a strong correlation between PDO warm phase and "signaling" migration. Salmon interaction with open ocean environment is scarce and adds difficulty in further studies. It may be possible that salmonids will migrate to environments they are not adapted for. In the last 100 years, approx. 40% of Pacific Salmon have disappeared from usual breeding grounds. It is possible to have migration away from the Northwest. While not favorable to salmon, it could be possible to have adaptability, unless there is a failure in another related food web or ecosystem that affects salmonid resources. Understanding ecological adaptability is a topic needing further research as it is currently limited.

Demand and Industry

Freshwater is a serious issue when regarding municipal uses. Gcrops, watering lawns, washing cars, and general use have a massive impact. Localities like Portland, a +2.0C increase can decrease minimum storage by 1.3 billion gallons, creating a deficit of 1.5 billion gallons. This leads to issues regarding how to reduce unnecessary usage.

Institutions and resource managers are reluctant to use seasonal forecasts, or additional data in conjunction with what they already have. Reasons varied, some of which said it outside the "scope" of their interests. The Army Corps of Engineers set how reservoirs are managed along with congressional guidelines they must follow. This puts the question of who should be in control, state or federal?

Further complications include competition during scarce times and overlapping geographic regions. The need to recognize what's most sensitive to clime change, create plans for adjustments and policies, then adapt. See figure below:

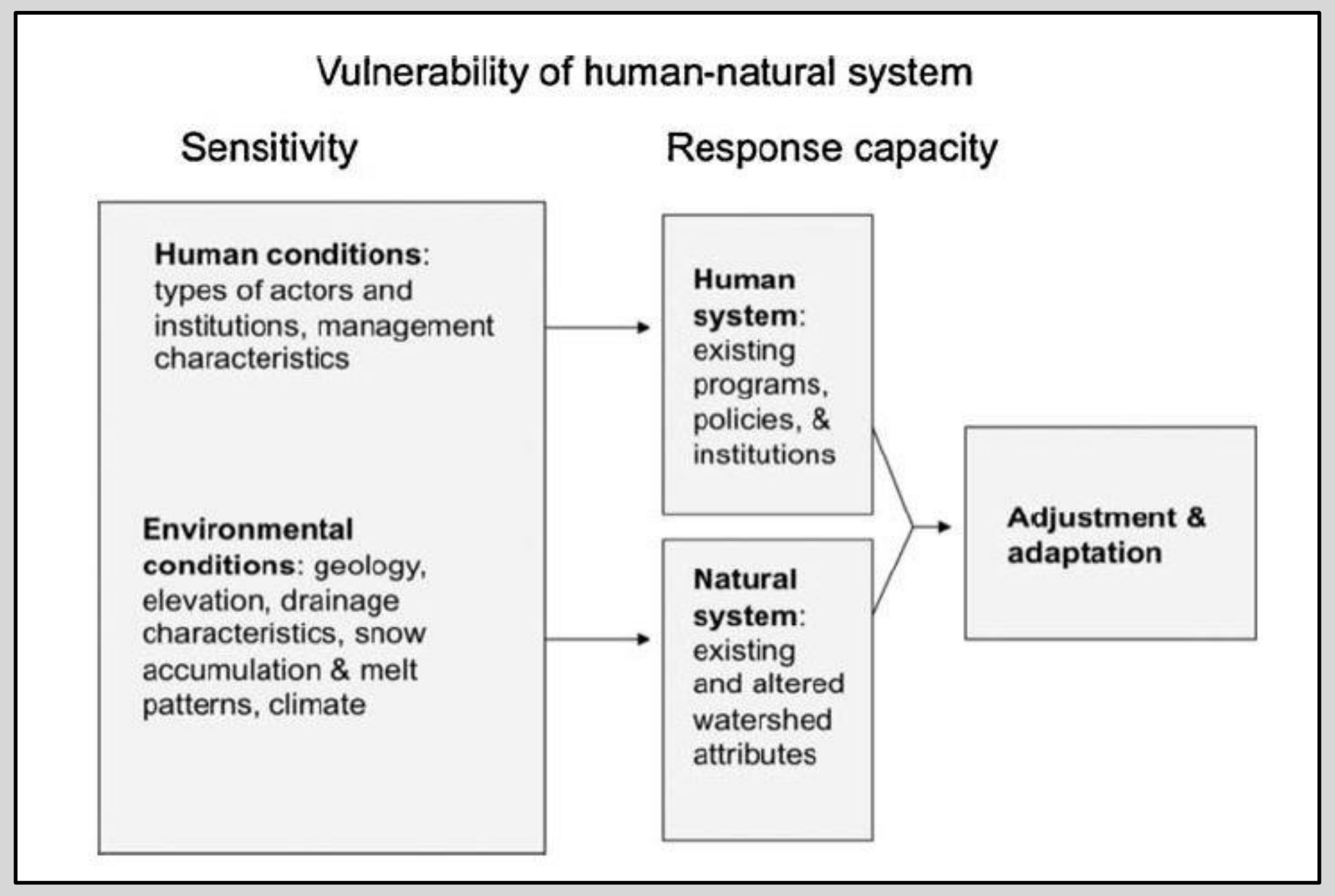

Figure 4. Conceptual model to recognize, predict, and plan for increasing adaptability (Farley, K.A., et. Al 2010)

Conclusion

Observed warming trends of the 20th century was +0.82° C showing increasing temperatures due to climate change. Models project possible warming of +0.5-2.5° C by 2020's and +1.5-3.2° C by 2040's. The regional effect on resources such as salmon, forests, and freshwater will be strained due to less snowpack as more winter snow falls as rain and earlier melting in the spring. Politics, institutional interests, and policies present complicated barriers in improving forecasting, recognizing sensitivities, and creating a plan for adaptability. The time to expand research, plan, and adjust policies regarding climate change is now and should be of high priority.

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Vulnerability of water supply from the Oregon Cascades to changing climate: Linking science to users and policy

Kathleen A. Farley [a,*], Christina Tague [b], Gordon E. Grant [c,d]

[a] *Department of Geography, San Diego State University, San Diego, CA 92182-4493, United States*
[b] *Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106-5131, United States*
[c] *US Forest Service, Pacific Northwest Research Station, USDA, Corvallis, OR 97331, United States*
[d] *Department of Geosciences, Oregon State University, Corvallis, OR, United States*

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McKenzie River

ABSTRACT

Despite improvements in understanding biophysical response to climate change, a better understanding of how such changes will affect societies is still needed. We evaluated effects of climate change on the coupled human–environmental system of the McKenzie River watershed in the Oregon Cascades in order to assess its vulnerability. Published empirical and modeling results indicate that climate change will alter both the timing and quantity of streamflow, but understanding how these changes will impact different water users is essential to facilitate adaptation to changing conditions. In order to better understand the vulnerability of four water use sectors to changing streamflow, we conducted a series of semi-structured interviews with representatives of each sector, in which we presented projected changes in streamflow and asked respondents to assess how changing water availability would impact their activities. In the McKenzie River watershed, there are distinct spatial and temporal patterns associated with sensitivity of water resources to climate change. This research illustrates that the implications of changing streamflow vary substantially among different water users, with vulnerabilities being determined in part by the spatial scale and timing of water use and the flexibility of those uses in time and space. Furthermore, institutions within some sectors were found to be better positioned to effectively respond to changes in water resources associated with climate change, while others have substantial barriers to the flexibility needed to manage for new conditions. A clearer understanding of these opportunities and constraints across water use sectors can provide a basis for improving response capacity and potentially reducing vulnerability to changing water resources in the region.

1. Introduction

Globally, the potential impact of climate change on water resources has been the subject of analysis for over a decade, and the Intergovernmental Panel on Climate Change (IPCC) has recently reported on accumulating evidence that freshwater resources are vulnerable globally (Bates et al., 2008). In the Western U.S., where many of the water supplies are currently over-allocated, water is one of the resources most vulnerable to climate change, as changes in the timing or quantity of streamflow have potential to further stress supplies (Barnett et al., 2005; Bales et al., 2006; Knowles et al., 2006). In particular, summer water shortages are predicted to worsen in response to climate change in many parts of the Western U.S., including the Oregon Cascades (Parson et al., 2001; Mote et al., 2003). Although less than 10% of annual streamflow occurs during July and August in this region, summer flows are particularly important for many of the water users there. At the same time, it is the flow most sensitive to alteration with climate change. As more precipitation falls as rain and snowmelt occurs earlier, a portion of the summer flow is shifted to winter and spring. Summer flows are also more vulnerable to increased evapotranspiration losses with warming.

One of the Cascades rivers where these types of changes are expected to occur is the McKenzie River, which spans an altitudinal range from over 3000 m at its eastern boundary to just over 100 m at its confluence with the Willamette River. The McKenzie provides water for commercial, industrial, and residential uses, and contributes to hydroelectric generation. In addition, it provides habitat for fish, including three federally listed species – bull trout, spring Chinook salmon, and Oregon chub – and recreational activities such as guided fishing on the McKenzie constitute

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[*] Corresponding author. Tel.: +1 619 594 8472; fax: +1 619 594 4938.
E-mail addresses: kfarley@mail.sdsu.edu (K.A. Farley), ctague@bren.ucsb.edu (C. Tague), gordon.grant@orst.edu (G.E. Grant).

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The Effect of Climate Change and Other Biological factors on the Willamette River Basin's (WRB) Future Water Balance

Curt Knott, cknott16@wou.edu, Natural Science Department, Western Oregon University, Monmouth, 97361

Western Oregon UNIVERSITY
Geology & Earth Science

Section 1: Abstract

Climate change is currently one of the largest issues that scientists and researchers have been combating over the last decade. These issues will lead to consequences if not carefully monitored. Climate change as a whole has been and will be affecting the US and the world

In the Willamette River Valley (Oregon), there are two primary causes for concern regarding future transpiration of water ; Increase in Carbon dioxide (CO_2), which closes the stomata of plants, and the increase in temperature, which in turn lowers the snow pack in the higher elevated areas of the basin. The program Envision was used to map many factors that contribute this assumption.

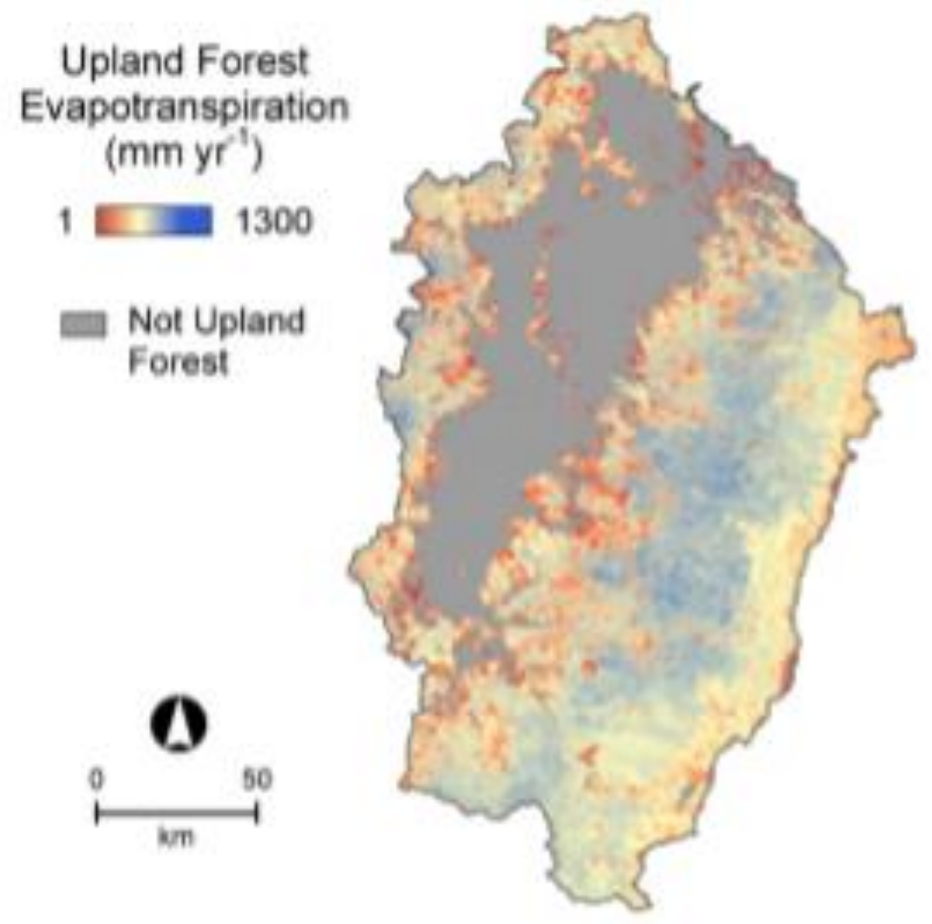
Approaching such a complex problem, many different sources of data are required. The Envision program was one of the mapping programs used, it mapped the land use and disturbances from human use. Another program was used to model all non-human occurrences. This includes rainfall, snowfall, canopy rain evaporation, canopy snow sublimation, transpiration, infiltration and runoff.

The Results of mapping the aforementioned variables and using a program to predict the future mean temperature, along with estimated rainfall as affected by climate change and changes in relatable variables, such as evapotranspiration (ET) yielded the following results. The model average showed increases in total precipitation and rainfall by 3% and 13% respectively (Turner, DP., see references) . On the other hand, ET, canopy rain evaporation decreased by 4% (Turner, DP., see references). The largest impacts where on Snowfall and canopy snow sublimation, which both decreased by more than 45% (Turner, DP., see references).

Section 2: Introduction

The Highlands within the Willamette River Basin (WRB) are the primary focus of this investigation. Considering that the highlands are the primary wooded area, it is important to consider total amount of transpiration that takes place within this part of the valley. The Leaf Area Index (LAI) is one of the methods of calculating the amount of leaves cover a certain amount of ground. LAI is defined as the one-sided leaf or needle per ground area. This is critical in calculating the Evapotranspirative rates of the trees within the region (see figure 2.1). Evapotranspiration is one of the key contributors to precipitation in the WRB highlands. Evapotranspiration (ET) is defined as sum of evaporation and plant transpiration from the earths surface (Wikipedia). The ET from plants is crucial in keeping the Vapor-pressure deficit low. The Vapor-pressure deficit (VPD) is the difference in the amount of water the air is currently capable of holding and the actual amount of water the air is currently holding. These three concepts are key terms that will be used throughout the investigation.

FIGURE 2.1: The Evapotranspiration and Area of the Upland Forest within the Willamette River Basin



The Human impacts also need to be taken into consideration when looking at future environmental changes, especially with the exponential rise in human population. Fire has been a menace in Oregon over the past few years due to fires. According to article one (see references, Turner, DP.), the amount of burned area could increase up to 9 times over.

Section 3: WRB Watershed Hydrology Model

The Watershed hydrology model is a concept that simplifies the complicated processes of a real world system. For the provided model, the following algorithms where used to simplify the individual variables (All formulas by Turner, DP., See References)

- **Precipitation (Rain and Snow):** All P=S when temperature is below -2 Celsius, all P=R when temperature is above 6 Celsius, where S = Snow and R = Rain
- **Canopy Transpiration and Soil Evaporation:** $VPD_{scalar} = (1-((VPD-VPD_{min})/(VPD_{max}-VPD_{min})))$ where the $VPD_{min} = .61$ MPa and $VPD_{max} = 3.10$ MPa. VPD_{scalar} was set to be 1.0 below VPD_{min} and set to a minimum of .02 as VPD approaches VPD_{max}. VPD is the Vapor-pressure differential mentioned in Section 2 . This is used to include conifer trees in the WRB.
- **Snow Melt:** $SW_t = e^{(LAI(-k))}$ is the formula used to calculate the transmittance through the canopy and the absorbability of snow. SW_t = Canopy radiation transmittance and the absorbance of snow, K = extinction coefficient which varies with latent heat of fusion variables.

Section 4: Discussion and Analysis

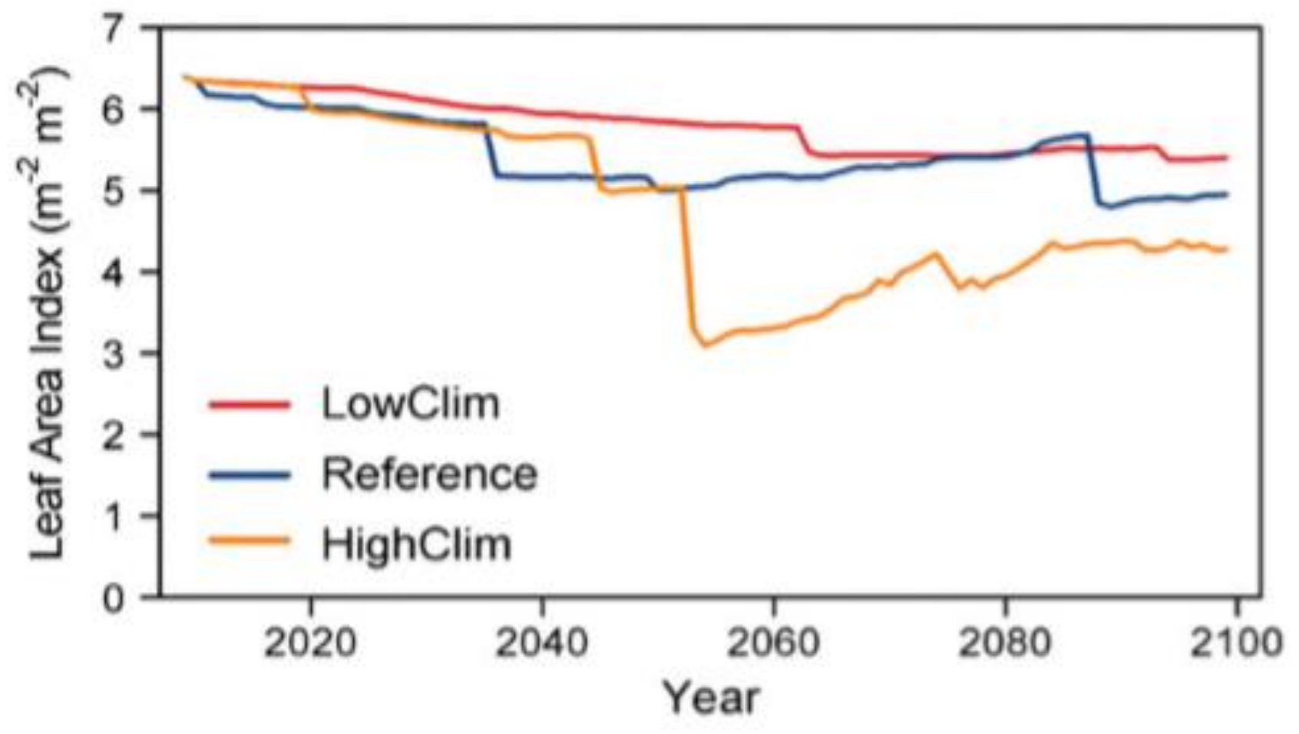
The effects of climate change on the ET and thus the water balance are extensive. The ET_{total} is declining due to decreasing amount of transpiration. CO_2 , one of the most condemned molecules on the planet, is also the culprit of the lowered transpiration in the plants. Stomata are small pores on the bottom of leaves that release water and oxygen during photosynthesis. The stomata in plants close under two conditions.

The first is if water is scarce, such as a hot summer day or in desert environments. This is caused by osmosis, which is the movement of water from a high concentration to a low concentration. Water concentration inside the plant is higher, which naturally causes the plant to release some of its water to the atmosphere. To prevent this, the plant closes its stomata.

The second reason for the closing of stomata is CO_2. Carbon dioxide is one of the required molecules for photosynthesis. However, when CO_2 concentration is to high, the stomata stop absorbing carbon dioxide to conserve water, since it is also one of the photosynthetic molecules.

This affect on the stomata causes plants to not function at their most efficient rate. As a result, some plants will no longer reproduce as well, or might even die out entirely. Lower vegetative density leads to a lower leaf area index (see introduction). The decrease in LAI from climate change greatly lowers the nightly ET, thus lowering the amount of water in the air at night. LAI also can be tied directly to the total number of plants in the area, and in the WRB highlands, trees have the highest biomass of any plant. This means that these trees are the most affected by this change in LAI.

FIGURE 4.1: The three different generated models for Leaf Area Index for the next 100 years



Lower tree populations leads to lowered canopy rain transpiration and snow sublimation because there are less trees to catch the precipitation from rainfall or snowfall. When the tree intercepts this precipitated water, it absorbs some of the caught water. This water is later released through transpiration, but this is not the only way water is returned to the atmosphere, it also evaporates directly off the tree due to increased sun exposure.

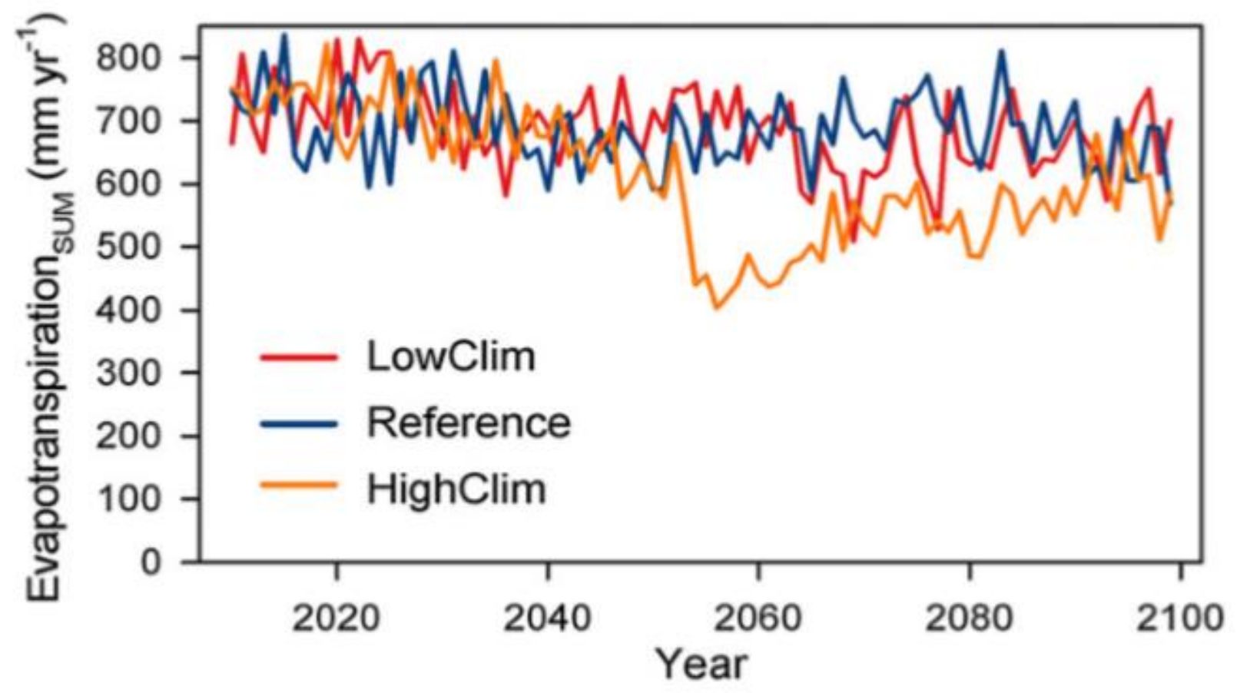
Section 5: Model

TABLE 5.1: Average Changes in Temperature, and different forms of precipitation

GCM Name	RCP	Δ MAT °C	Δ P (annual) % (mm)	Δ P (JJA) % (mm)	Δ P (JFM) % (mm)	Acronym
GFDL-ESM2M	4.5	1.2	0 (0)	-15 (-15)	9 (49)	LowClim
MIROC5	8.5	3.6	4 (66)	5 (5)	13 (71)	Reference
HadGEM2-ES	8.5	5.3	1 (17)	-3 (-3)	8 (44)	HighClim

- The model to the right shows the raw change in data over the entire simulated timeframe. The Reference includes the average expected values.

FIGURE 5.2: The estimated rates of Evapotranspiration totals per year for each of the modeled situations



- As seen in Figure 5.2, the HighClim has the lowest evapotranspiration, while the reference and the LowClim are reasonably close to one another. Evapotranspiration on HighClim gets as low as 400mm/yr.

Section 6: Conclusion

Considering the models, it is likely that the future climate of the Willamette River Basin will become warmer during the winter, which will be accompanied by higher rates of precipitation in the form of rain. Similarly, the summers will also experience an increase in temperature. Unlike in winter, the summer will probably experience a decrease in precipitation due to the lower rate of evapotranspiration from CO_2 increases.

Although naturally, the vegetative density should be similar to the way it is now, logging increases and the threat of fire will cause a gradual decrease in the leaf area density. Decreases in Leaf Area Index will be one of the leading influence on evapotranspiration, canopy rain evaporation, and canopy snow sublimation. Canopy snow sublimation will likely already be extremely hindered by the increase in temperature.

Vapor-pressure deficit and high CO_2 values will also influence the evapotranspiration when vegetation is taken into consideration. The Vapor-pressure deficit will increase as the CO_2 concentration increases. CO_2 closes the stomata in leaves when the concentrations are to high, this lowers the amount of transported water, and thus lowers the Vapor-pressure deficit.

The predicted decrease in evapotranspiration due to lower leaf area index and increased Vapor-pressure deficit is an issue that needs to be attended. The increase in human activity is one of the most solvable problem. Logging is can be kept more constant instead of increasing demand, fire safety can be implemented more firmly to decrease the risk of fires, and hopefully these lesser impacts from humans can keep the leaf area index and the vapor-pressure deficit constant so that the WRB highlands remain forested, healthy, and abundant in water.

Section 7: References

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WILEY

RESEARCH ARTICLE

Assessing mechanisms of climate change impact on the upland forest water balance of the Willamette River Basin, Oregon

David P. Turner[1*] | **David R. Conklin**[2] | **Kellie B. Vache**[3] | **Cynthia Schwartz**[3] | **Anne W. Nolin**[4] | **Heejun Chang**[5] | **Eric Watson**[5] | **John P. Bolte**[3]

[1] Department of Forest Ecosystems and Society, Oregon State University, Corvallis, Oregon 97331, USA

[2] Oregon Freshwater Simulations, Portland, Oregon 97213, USA

[3] Department of Biological and Ecological Engineering, Oregon State University, Corvallis, Oregon 97331, USA

[4] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA

[5] Department of Geography, Portland State University, Portland, Oregon 97201, USA

Correspondence
David Turner, Department of Forest Ecosystems and Society, Oregon State University, Corvallis, Oregon 97331, USA.
Email: david.turner@oregonstate.edu

Abstract

Projected changes in air temperature, precipitation, and vapor pressure for the Willamette River Basin (Oregon, USA) over the next century will have significant impacts on the river basin water balance, notably on the amount of evapotranspiration (ET). Mechanisms of impact on ET will be both direct and indirect, but there is limited understanding of their absolute and relative magnitudes. Here, we developed a spatially explicit, daily time-step, modeling infrastructure to simulate the basin-wide water balance that accounts for meteorological influences, as well as effects mediated by changing vegetation cover type, leaf area, and ecophysiology. Three CMIP5 climate scenarios (Lowclim, Reference, and HighClim) were run for the 2010–2100 period. Besides warmer temperatures, the climate scenarios were characterized by wetter winters and increasing vapor pressure deficits. In the mid-range Reference scenario, our landscape simulation model (Envision) projected a continuation of forest cover on the uplands but a threefold increase in area burned per year. A decline (12–30%) in basin-wide mean leaf area index (LAI) in forests was projected in all scenarios. The lower LAIs drove a corresponding decline in ET. In a sensitivity test, the effect of increasing CO_2 on stomatal conductance induced a further substantial decrease (11–18%) in basin-wide mean ET. The net effect of decreases in ET and increases in winter precipitation was an increase in annual streamflow. These results support the inclusion of changes in land cover, land use, LAI, and ecophysiology in efforts to anticipate impacts of climate change on basin-scale water balances.

KEYWORDS

climate change, evapotranspiration, forest, hydrologic model, Oregon, water balance, Willamette River Basin

1 | INTRODUCTION

In forested catchments, the magnitude of evapotranspiration (ET) is often a large proportion of precipitation (Chang, Johnson, Hinkley, & Jung, 2014) and thus is a significant control on delivery of water as streamflow for human purposes. Climate change is expected to alter ET in complex ways, notably by increasing the evaporative demand of the atmosphere, influencing the characteristics of the precipitation, and changing the vegetation. Distributed hydrologic models offer the opportunity to examine potential impacts of climate change on upland forest ET, but commonly, they do not account for changing vegetation (e.g., Tohver, Hamlet, & Lee, 2014). Here, we couple a fine spatial resolution landscape simulation model (that treats changes in land cover, land use, and leaf area), with a process-based, spatially distributed hydrology model. This combination permits assessment of multiple interacting mechanisms by which climate change might impact ET and streamflow.

The importance of vegetation changes (principally associated with disturbances) to ET and streamflow has been documented in the context of harvesting (Abdelnour, Stieglitz, Pan, & McKane, 2012), wildfire and prescribed burns (Stoof *et al.*, 2012), and insect outbreaks (Bearup, Maxwell, Clow, & McCray, 2014). Generally, a reduction in leaf area index (LAI) results in an increase in streamflow. Mechanisms accounting for that increase include reduction of transpiration, reduction in evaporation of canopy-intercepted rain, and reduction in sublimation of canopy-intercepted snow (Bearup *et al.*, 2014, Chen *et al.*, 2015, Nanko, Onda, Kato, & Gomi, 2015). More subtle changes in vegetation, as in reduction of stomatal density (and conductance) in response to

The Effects of Forest Fire on Snow Albedo

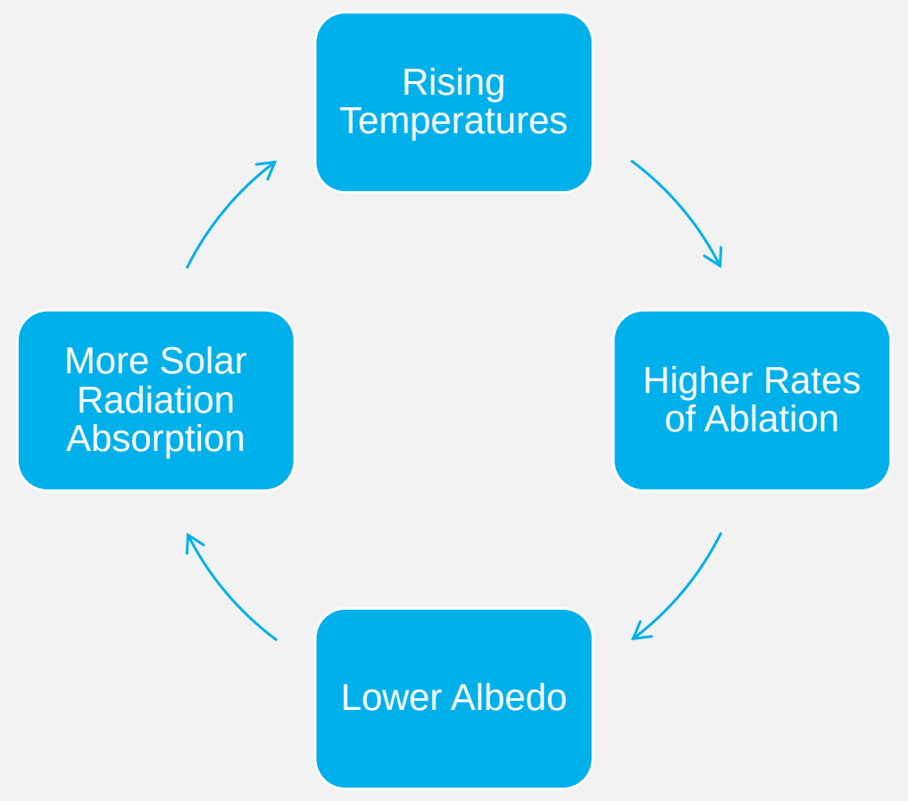
ES476 Hydrology Journal Review by Emily Carlston | Western Oregon University

Introduction

In the Pacific Northwest there is a high demand for water year round due to the ever increasing uses. The Willamette Valley gets the majority of water resources through snowpack that builds up gradually during the winter and melts slowly over the summer creating a steady input of water. One of the sources of these snowpack is found on the Cascade range, but something changes when the natural processes of forest fires come into effect. The dynamic relationship of ablation, albedo, and forest fires triggers a relentless feedback loop. These three papers will explore the possible ramifications of forest fires and their role in water resources and climate change.

Background Information

In order to discuss this feedback loop, the parts of the feedback loop must be identified.



Rising Temperatures

Higher Rates of Ablation

Lower Albedo

More Solar Radiation Absorption

- Albedo is defined as the reflective properties of snow.
- Ablation is the removal of snow through any method such as melting or sublimation.
- Forest fires are an expanse of unrestrained fire occurring in a natural area.

The snowpack as a water resource has a large impact on not only the local environment, but also the local economy. If the snowpack continues to disappear over a larger region it will begin to have a higher impact on the interlinked global climates. A forest fire's effect on both the albedo and the ablation through reduced canopy cover, as well as increased debris and a darkening of the area, create an acceleration of snowpack melt. The stress of not only forest fires, but also other natural and anthropogenic forces will speed up this impact.

Discussion

In comparison, all of these different studies were going about tackling the same problem from different views and combined identify the different aspects of the overall feedback loop. Forest fires increase this feedback loop and can inversely trigger changes in the overall climate change. Higher rate of ablation are seen from the decrease of forest canopy cover due to forest fires. Dark debris generated by the fires also create a decrease in albedo, increasing the overall solar radiation. This leads to an overall decrease in snowpack, further edging along the feedback loop do to an increase in temperatures. In the high cascades this decrease in snow can lead to more drought and stricter rules on water resources.

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Methods

The Response of Northern Hemisphere Snow Cover to a Changing Climate*
Ross D. Brown and Philip W. Mote

There are a lot of different data sources for the western hemisphere. This study used for data sources to look at the change in time over specific areas of study. The data sources were collected from:

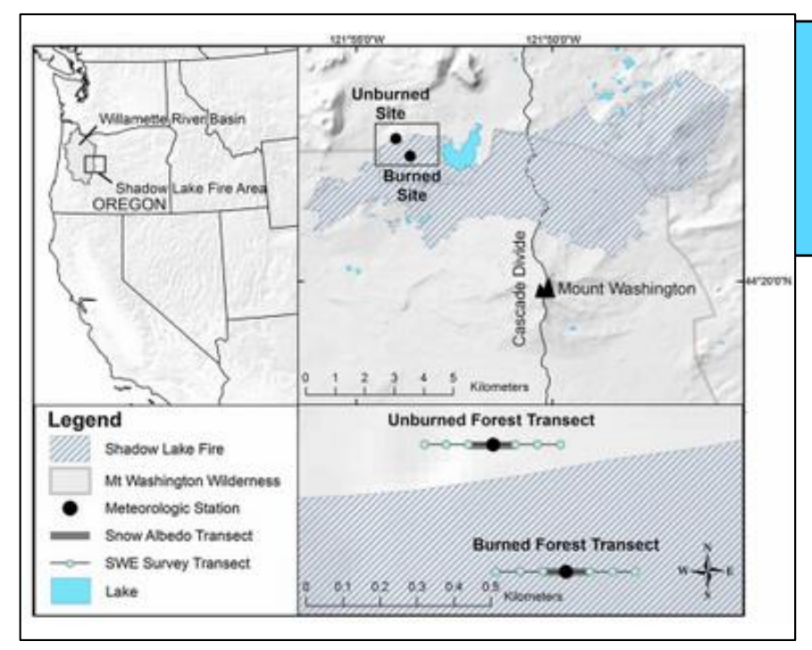
- The Climate Station data from four Canadian sites from 1961-1990
- NOAA Satellite Snow Cover Extent that examined snow cover trends from 1966-2007
- World Climate Research Program's CMIP3 Multi-model Dataset
- Northern Hemisphere Snow Water Equivalent Climatology

The datasets were then examined individually to provide a potential indicator for climate change based on the properties of snowmelt.

Charred forests increase snowmelt: Effects of Burned Woody Debris and Incoming Solar Radiation on Snow Ablation
Kelly E. Gleason, Anne W. Nolin, and Travis R. Roth

The McKenzie headwaters river basin is the main focus of this study, with around 50% of the area burned with a moderate-high burn severity leaving a near total loss of forest canopy coverage, this locality on the Oregon High Cascades was the perfect spot to observe the snowmelt. This particular river basin, with an elevation of 1750 m, is a tributary to the Willamette River and receives around 300 cm of precipitation between November and April.

The hourly mean incoming and outgoing solar radiation was collected and used to calculate the ratio of snow albedo in areas were accumulation exceed 30 cm. Inside of the plot, sample areas 0.5 km transect were made. Within the transect snow depth and snow water equivalent were measured at the lowest resolution of 100m monthly with increasing frequency towards the end of melt season. At each data collection location for snow water equivalent, a sample of surface snow was taking to look at debris filtration. Within each transect a Riegl VZ400TM terrestrial laser scanner was used to collect information about tree high, crown radius and overall forest density. This data was then combine with areal visualizations created by CycloneTM and ArcGISTM. Using



Burned and unburned forest sites are located in the Shadow Lake Fire area.

The Oregon ForEST network sites of the McKenzie River basin.

Forest Impacts on Snow Accumulation and Ablation Across an Elevation Gradient in a Temperate Montane Environment
Travis R. Roth and Anne W. Nolin

Taking place in the McKenzie River basin (MRB), this study used six different sampling sites that used two different forest covers, low forest density 20% canopy cover and high forest density 60 % canopy cover, at three different elevations: Low (1150 m), Mid (1325 m), and High (1465 m). The canopy cover requirements were based on the 2001 National Vegetation Cover Database. The forest density was determined by the plotless density estimator approach and hemispherical photographs taken with a Nikon Coolpix 990 digital camera using a FC-E8 fisheye converter gave a 180° field-of-view. A Gap Light Analyzer 2.0 was then applied to measure leaf area index (LAI) and canopy closure (CC). The snow water equivalent was measured along a 900 m transect and were collect monthly with an increase in collection rates near the snow disappearance date.

Results

The Response of Northern Hemisphere Snow Cover to a Changing Climate*
Ross D. Brown and Philip W. Mote

Throughout all of the datasets there was a heavy implication put on the amount of snow coverage present at various given areas in the Northern Hemisphere. Statistical analysis was then used to correlate the increases in air temperature and the amount of precipitation. In the first dataset Tahtsa Lake exhibited the strongest temperature sensitivity. Significant reductions in snow water equivalent max are more likely to occur in the lower elevations of maritime climates. From these results possible projections were made for the upcoming years.

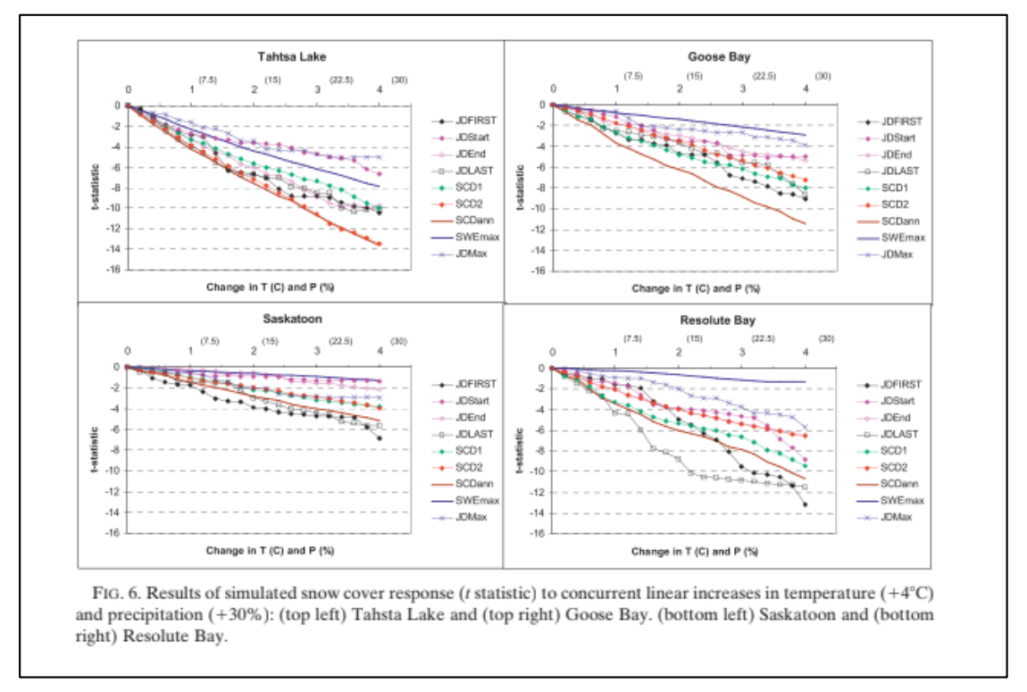
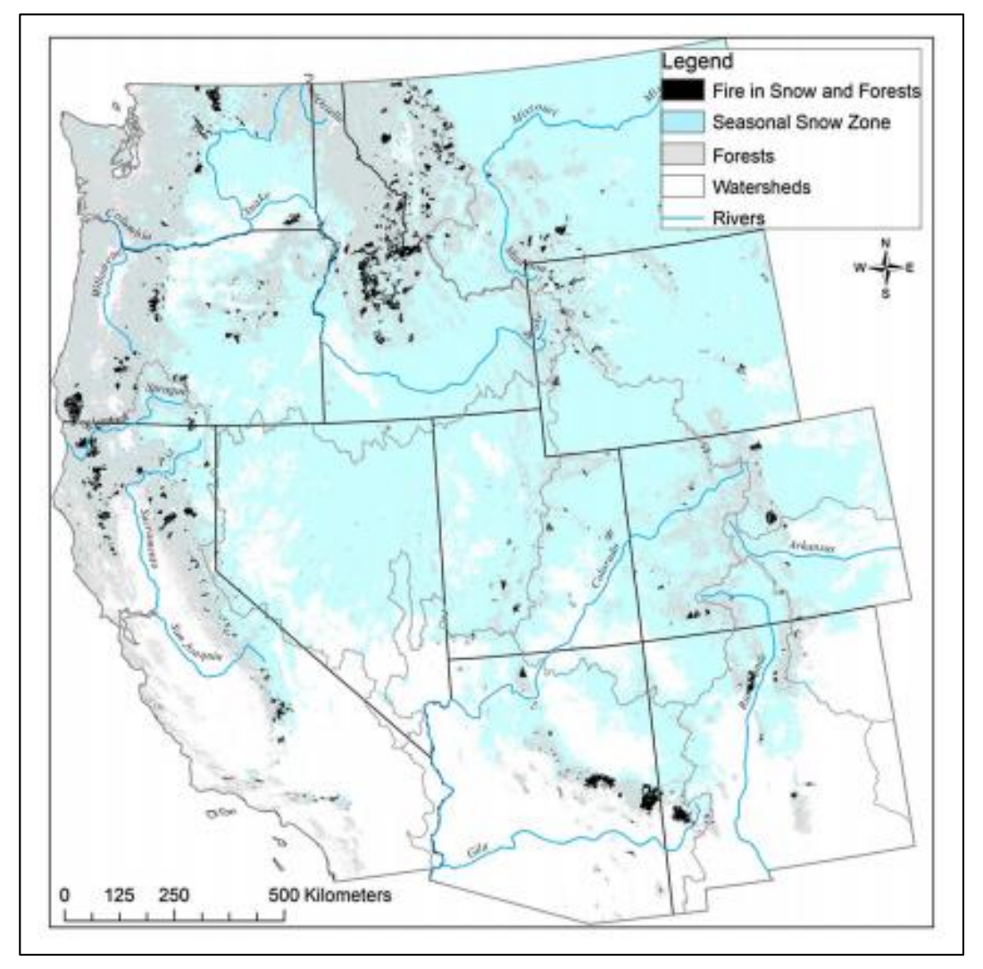


FIG. 6. Results of simulated snow cover response (t statistic) to concurrent linear increases in temperature (+4°C) and precipitation (+30%): (top left) Tahsta Lake and (top right) Goose Bay. (bottom left) Saskatoon and (bottom right) Resolute Bay.

Results of simulated snow cover response (t statistic) to concurrent linear increases in temperature (148C) and precipitation (130%): (top left) Tahsta Lake and (top right) Goose Bay. (bottom left) Saskatoon and (bottom right) Resolute Bay.



Forest fire area overlapping the seasonal snow zone in the western United States (2000–2012).

Charred forests increase snowmelt: Effects of Burned Woody Debris and Incoming Solar Radiation on Snow Ablation
Kelly E. Gleason, Anne W. Nolin, and Travis R. Roth

During accumulation there was no difference in albedo, but as time went on there was a significant difference. Areas with burned woody debris had a decrease in albedo around 40% and the mean solar radiation was around 60% greater than that of unburned forest. Burned areas were also likely to hold than double the mean debris concentration. Debris concentration is defined as the grams of debris per kilogram of snow. Forest fires were found to be larger inside of the season snow zone than outside of it and after 2000 there have been over 44,000 square kilometers of forests burned in these areas.

Forest Impacts on Snow Accumulation and Ablation Across an Elevation Gradient in a Temperate Montane Environment
Travis R. Roth and Anne W. Nolin

During a water year in this watershed, substantial differences in accumulation and ablation can be seen when combining the various factors of altitude and forest cover. Results from the water years of 2012 to 2015 shows that canopy interception efficiency was significantly lower in higher altitudes while remaining fairly similar between the lower ones. Net radiation was a key factor in all areas, with the shortwave radiation being dominate where as longwave radiation only being seen in open areas. The forest canopy coverage has a great impact of the distribution of solar radiation onto an area. Solar shading has a relevant position in decreasing the amount of solar inputs.

Conclusion

If this feedback loop continues, ablation and albedo will only continue to reinforce each other, eventually leading to an increase in temperatures and drought frequency. The inability to have a closed system that can be controlled in every aspect only drives a larger need for preventative fire safety, such as controlled burns and expansive comprehension on our local water budget. There needs to be a drastic intervention in the way we think about our water budget and the natural and anthropogenic processes that affect it.

GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 4654–4661, doi:10.1002/grl.50896, 2013

Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation

Kelly E. Gleason,[1] Anne W. Nolin,[1] and Travis R. Roth[1]

Received 12 June 2013; revised 19 August 2013; accepted 20 August 2013; published 10 September 2013.

[1] We document effects of postfire forest conditions on snow accumulation, albedo, and ablation in the Oregon Cascades. We measured snow water equivalent, solar radiation, snow albedo, and snowpack surface debris at a pair of burned and unburned forest plots. Snow accumulation was greater in the burned forest; however, the snowpack disappeared 23 days earlier and had twice the ablation rate than in the unburned forest. Snow albedo was 40% lower in the burned forest during ablation, while approximately 60% more solar radiation reached the snow surface, driving a 200% increase in net shortwave radiation. Significant amounts of pyrogenic carbon particles and larger burned woody debris shed from standing charred trees accumulated on the snowpack and darkened its surface. Spatial analysis showed that across the Western U.S., 80% of all forest fires occurred in the seasonal snow zone, and were 4.4 times larger than fires outside the seasonal snow zone. **Citation:** Gleason, K. E., A. W. Nolin, and T. R. Roth (2013), Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation, *Geophys. Res. Lett.*, *40*, 4654–4661, doi:10.1002/grl.50896.

1. Introduction

[2] In the montane western United States, most annual precipitation falls as snow [*Serreze et al.*, 1999], yet rising temperatures have reduced snowpacks [*Abatzoglou*, 2011; *Brown and Mote*, 2009; *Knowles et al.*, 2006; *Mote et al.*, 2005; *Pederson et al.*, 2013]. Key consequences of this have been increases in wildfire frequency, size, intensity, and duration across the western U.S. [*Westerling et al.*, 2006]. Total burned area in the western U.S. is anticipated to increase [*Littell et al.*, 2009; *Moritz et al.*, 2012; *Westerling et al.*, 2011] as a result of climate change and fire suppression [*Marlon et al.*, 2012].

[3] Forest fire affects patterns of snow accumulation and ablation by reducing canopy interception, increasing light transmission, and modifying the surface energy balance [*Burles and Boon*, 2011; *Harpold et al.*, 2013; *Winkler*, 2011]. Previous work showed that snow ablation rates are accelerated as much as 57% and snow disappeared 4–15 days earlier in a burned forest [*Burles and Boon*, 2011; *Skidmore et al.*, 1994; *Winkler*, 2011], but these studies omitted measurements of burned debris and its effect on snow spectral albedo. The objective of this paper is to demonstrate how charred forests decrease snow albedo through debris deposition, and how when combined with increased solar radiation, this leads to earlier snow disappearance.

[4] Because snow is highly reflective in the visible wavelengths (400–700 nm), even a small decrease in visible albedo will dramatically increase net shortwave radiation [*Dozier et al.*, 2009]. Previous work has shown that light absorbing impurities in snow, such as dust and soot, can lead to substantial radiative heating and faster snow melt rates [*Flanner et al.*, 2009; *Painter et al.*, 2012; *Painter et al.*, 2007; *Skiles et al.*, 2012]. Compared with mineral dust, carbon soot is an order of magnitude more effective at absorbing solar energy in the visible wavelengths [*Warren and Wiscombe*, 1980]. Although far more coarse than dust and soot, debris from the forest canopy accumulates on the snowpack and reduces albedo [*Hardy et al.*, 2000; *Melloh et al.*, 2001]. For decades after a fire, burned woody debris (BWD) including pyrogenic carbon [*Preston and Schmidt*, 2006], charcoal, charred woody detritus, and partially charred needles, cones, and bark are shed from standing burned trees onto the snowpack [*Dunn and Bailey*, 2012]. While it is visibly apparent that BWD darkens the snow surface (Figure 1), the effects on snow spectral albedo and snowpack ablation have not been quantified. This investigation provides the first measurements of snow spectral albedo and snow surface BWD in a burned forest, and provides evidence for the impacts of wildfire on snow accumulation and ablation.

2. Site Description

[5] The study area is located in the Oregon High Cascades at an elevation of 1750 m, in the headwaters of the McKenzie River Basin, a major tributary to the Willamette River. This area receives approximately 3000 mm of precipitation a year, most of which falls as snow from November to April [*Taylor and Hannan*, 1999]. In late summer 2011, the Shadow Lake Fire burned 42 km^2 of High Cascades mixed conifer forest [*Franklin and Dyrness*, 1973] in the Willamette and Deschutes National Forests (Figure 2). About 50% of the area burned with moderate-to-high burn severity, with near total loss of forest canopy (Figure 3). This location serves as an ideal field laboratory for our paired study of snowpack dynamics and snow albedo in a severely burned forest (BF) plot and in an adjacent, unburned forest (UF) plot.

3. Research Methods

3.1. Measuring Postfire Snow Spectral Albedo and Net Radiation

[6] Snow spectral albedo was measured every 20 m along a 200 m transect in the burned and unburned study sites using an Analytical Spectral Devices Full-Range Portable Field

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[1] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.

Corresponding author: K. E. Gleason, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, 104 Wilkinson Hall, Corvallis, OR 97331, USA. (gleasoke@science.oregonstate.edu)

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