November 30, 2020

To: HESS Editor

From: Chas Jones, PhD

Subject: Reconciliation of manuscript by Jones et al. (hess-2019-638)

Thank you for offering us the opportunity to respond to the reviewers' comments and feedback on our manuscript titled "Using hydrologic landscape classification and climatic time series to assess hydrologic vulnerability of the Western U.S. to climate". The manuscript was reviewed by one reviewer (RC2) that recommended that the paper be "revised and resubmitted". A second reviewer (RC1) suggested changing the manuscript into a technical note. We have addressed the specific concerns in the attached revision that improves the manuscript and makes it worthy of publication in HESS. We found the reviewer feedback to be insightful and it benefitted the manuscript. Attached you will find a copy of our response to the two reviewer comments and one short comment

Please note that the reviewer line numbers reference the original manuscript submitted to HESS, while the response line numbers refer to the unmarked-up version of the revised manuscript.

Reviewer Comments (Submitted as RC2)

1) General Comment

   This paper aims to apply the hydrologic landscape approach to chronicling changes to the western U.S. under climate change. Using a vulnerability index, the authors aim to highlight locations more or less prone to changes in climate for various indices. It is apparent that the manuscript was a technically challenging effort to reconcile multiple datasets and climate scenarios and synthesize them in a GIS framework. The work there should not be discounted. The manuscript is generally well written but feels disjointed and an attempt to reconcile several disparate research efforts between a discussion on climate change, hydrologic landscapes, and vulnerability of socially/economically valuable locations. I understand what the authors are aiming for. If the authors aim to show all three aspects, they could be better unified. Overall, I think this paper is worthy of publication and the data analysis is commendable, but better structure and explanation is needed. I recommend the paper be revised and resubmitted.

   > *Response) Thank you for this feedback and recognition of the value of the research effort. RC2 recognizes that a strength of the manuscript is our attempt to integrate the fields of 1) climate change, 2) Hydrologic Landscape classification, and 3) the socioeconomic impacts of climate change. We highlight this strength of the analysis by adding/modifying the introduction which helped to emphasize these aspects of the study (L53-58; L138-145; added Section 4.2; and Section 5). We also added language of this unifying concept into the Introduction and then revisit the unifying concept in the closing paragraphs of the Discussion or Conclusion sections.*

2) Specific Comment (Lines 64-65)

"The findings are consistent across studies in many areas of the globe...." How are they consistent across studies and which studies? And the second half of this sentence seems to contradict the first half when you say they aren't consistent without any citations being given. Which one is it?

> *Response) This sentence is referring to McAfee's 2013 study and was intended to summarize her findings. We clarified the text to indicate that they found that regional analyses were more inconsistent than national studies. (L68-70)*

3) Specific Comment (Line 175-177)

   The methods describe that Leibowitz et al (2016) used a modification of Wigington et al (2013). It's a little unclear as to what the modification was. More clarity or explanation needed here.

   > *Response) We added text to summarize Leibowitz et al. (2016)'s modification to the Wigington et al. (2013) methods (L190-196).*

4) Specific Comment (Section 2.3)

   I'm a little unclear as to the selection of these dates and selection of data. Why is 1971-2000 considered the modern climate normal when such data is at least 20 years ago? It seems incongruous to have this be your ""modern"" normal when you consider "historical" data to be up to at least 2010 and state that the PRISM data you use for your calculation of modern normals goes from 1895-present. Why not have the modern normal represent a more recent time period?

   > *Response) Thank you for pointing this out. We agree that the use of the term "modern" is inaccurate and we have removed it throughout the document. We chose to use the 1971-2000 period because the analysis complemented the Leibowitz et al. 2016 study, which used 1971-2000 as its defined "climate normal." We added explanatory text to our reasoning for defining our normal climate period as 1971-2000 (Section 2.3.1). We have also removed references to the "modern" climate normal throughout the manuscript.*

5) Specific Comment (Section 2.3; Lines 230-240)

   I'm also unclear as to why monthly precipitation and mean temperature data is acceptable for the modern climate normal calculation (L230-232), but daily measurements are needed for the historical decadal analyses (L240) and they're subsequently averaged to monthly means anyways. The requirement for daily data caused you to employ a downscaling approach, potentially introducing more error. More explanation is needed here.

   > *Response) While we alluded to this detail in the original manuscript, we added explanatory text that clarifies the reasons for these decisions (Section 2.3.2). As far as error from downscaling, while the 400m data clearly have greater resolution and less error than the 4km data, for the actual application these data were aggregated to assessment units with a mean area of 56 km^2. So, in practice, the larger 4km resolution of the downscaled historical analysis should still be appropriate for the scale of the assessment units.*

6) Specific Comment (Lines 262-265 and Fig. 2)

   Better explanation is needed as to what were the criteria for choosing the 10 modeled emissions scenarios. Figure 2 appropriately shows their distribution in terms of precipitation and temperature, but how were the 10 out of the at least 38 chosen? Random draw? Some other selection criteria? Further, the coloring and subscript numbers in Figure 2 needs to be better explained in the caption.

   > *Response) We now explain that we subjectively selected ten models that appeared to span the entire range of predicted climatic responses of the full ensemble in a distributed manner (L284-286). We also added clarifying information about the figure coloring and naming conventions of Fig. 2 to its caption.*

7) Specific Comment (Section 2.5; Lines 309-316)

   Better explanation is needed for how these sites were selected and how their areal extent was decided (see Table 2). Site specific areal extent appears to range from 38 km2 to 4855 km2 (Table 2). Also, according to section 2.2 the target AU size is 80 km2 meaning that at the low end (e.g. Great Basin NP w/ area of 38 km2) is likely composed of a single AU and many only a few units. I get the challenges of making AUs a representative size across multiple different spatial datasets, but some discussion of how that AU size and differential location areal extent affects these location-based analyses is warranted.

   > *Response) Specific sites were selected subjectively so that we could examine climate impacts at sites that may be of general interest. In addition, the range of Assessment Unit (AU) areas represents watersheds that are larger than hillslopes but smaller than large basins. We also explain that all of the AUs that had their centroid within the geographic boundary of a location were included in the AU analysis for each location. For instance, the Great Basin National Park (GBNP) was covered by a single AU, rather than numerous AUs because the centroids contained by other AU areas fell outside of the GBNP boundary. We added explanatory language to explain all of this background information (Section 2.5).*

8) Specific Comment (Lines 312-313)

   "The time series for the decadal averages for each of the seven HL metrics..." I think you mean to say the seven climate related HL metrics here because things like elevation, subsurface permeability, and surface permeability aren't subject to change under this approach.

   > *Response) Thank you for the good catch. We added the 'climate-related' descriptor to our reference to the seven HL metrics (L341-342).*

9) Specific Comment (Lines 325-327)

   The sentence beginning "In terms of the 1971-2000 climate normal period" needs some revision. I think it needs a clause saying, "followed by 24% of the area showing fall seasonality, 13% spring seasonality. "

   > *Response) Absolutely. That was an awkward sentence that needed to be revised. The sentence structure has been improved as suggested (L354-356).*

10) Specific Comment (Lines 342-343)

Needs some clarification. What remaining models? You said in methods you only tested 10 and in the preceding text you said 3 may be wetter and 7 generally drier. What models are left?

Response) Thank you for noticing that duplication of information that basically repeated the information with different wording. We have deleted the duplicative text and relocated this subsection to the supplemental materials per comment #21.

11) Specific Comment (Line 355)

Several times in the results and discussion you point out patterns shown along major geographic features like mountain ranges (just as one example paragraph beginning on L351). It would be beneficial to show where those are like you do in the ecoregions in Figure 1. Many of the readers may be unfamiliar with where these features are so it makes it difficult to place the patterns you're describing.

Response) In this paragraph, we do reference the White Mountains, which is Location #42 in Fig. 1 and table 2. We believe that we've only referenced place names that correlate to Locations identified in Table 2 or Fig. 1. We have added a reference to the assigned Location # when referencing place names (Fig. 1). We also refer to the "Sierra-Nevada Mountains", "Cascade Mountains", and "Mountainous areas in Idaho" [L461-463]. We improved this issue by either modifying these references throughout the manuscript.

12) Specific Comment (Line 371)

Several times the authors talk about the sensitivity or vulnerability changes without talking about the direction of that change (but see sentence beginning on L371 "The map for S'" as an example). It'd be useful to make sure if you're saying an area is vulnerable to a change in climate, it's not just the metric (e.g. temperature) but also whether higher/lower or earlier/later.

Response) While it is possible to talk about direction of change (higher or lower than the two standard deviations) for the projection of an individual climate model, the vulnerability index is the integration of ten individual models. It is possible for individual models to exceed the two standard deviation threshold from the mean in both the upper and lower directions, thus there is not a unique direction of change associated with our vulnerability index as we've defined it. We added text to the methods and results that clarifies this detail of our Vulnerability Index (L316-319, 364-368; Section 4.1).

13) Specific Comment (Line 385-392)

I mentioned in my introduction that the paper was one that seemed disjointed between the paper being primarily one communicating climatic changes with a discussion of HLs and vulnerability thrown into the mix. This is an example of where the authors do a good job of uniting at least the HL approach with the climate indices. The HL approach is the story of the complete code where certain indices may play a more proximal role in given locations. This section does a good job of explaining how the changes in the climate indices could have differential effects based on things like elevation or the permeability metrics. More discussion like this is needed throughout the paper.

> *Response) Thank you for pointing out that the integration of the HL approach with the climate indices is a unique aspect of our manuscript and is worth expanding upon. We have added more text and additional HL context to our intro, discussion of climate and the associated socio-economic implications to the introduction, discussion, and/or conclusions. (L53-58; L138-139; L446-450; added section 4.2; and L538-540)*

14) Specific Comment (Figures 3 & 4)

These colors are hard to discern with much of the area looking a yellow color that according to the sale is no change. I wonder if more of a categorical variable would be appropriate here to show changes rather than a color ramp. The reddish hue is more noticeable in Figure 4 for sure, but I wonder if this could be better communicated.

> *Response) We appreciate the reviewers concern. However, Figures 3 and 4 do illustrate the actual geographic differences in FMI across large regions. Further, when mapping the differences categorically, the differences either appear exaggerated or absent. Thus, we prefer to retain these figures in their current form, as we consider categorical differences to be less accurate. However, we have pushed these results to the supplemental materials to shorten the manuscript and address reviewer comments.*

15) Specific Comment (Figure 7.1)

I wonder if here too classed variables may be better used to show variability by placing then in a low, medium, high type construct rather than a color ramp.

> *Response) We agree. We modified the images / legend as a classified variable.*

16) Specific Comment (Figure 8)

I'm confused by several aspects of this figure. Several of the figure panels don't have corresponding descriptions in the caption. For instance, there's a two separate panels for April 1 SWE and Snow, but the figure caption says "snow (April 1 SWE (mm))" as if they're combined somehow. This is confusing especially when the "Snow" panel has a y-axis labeled 1-2000 without any units. Also, the panel labeled "Climate" I believe is referenced as "FMI" in the caption. Also, on this panel the left y-axis is from -1 to 1 while the right axis is the categorical Arid-Very wet labels. This needs to be better explained as it's confusing even to someone familiar with HLs. Finally, the climate projection section is also confusing as sometimes it appears there's two lines while others there are several (e.g. Mt. Hood SWE panel). It may be cleaner to just show the high and low range lines rather than all the model scenarios I think you're showing. What the gray shaded area is showing also needs to be described in the caption.

> *Response) Thank you for the attention to detail. There was an error in the labeling of one of the figures. The "Snow" figure has been relabeled as "PET". We added clarification to the Climate / FMI panel of figures to address the reviewer's questions. At this time, we have chosen not to remove the red dashed lines that illustrate the individual climate model outputs.*

17) Specific Comment (Lines 426-521)

The discussion of the site-specific locations seems a bit disjointed in the discussion. I wonder if it'd be better served to be called out as case studies in a subsection. The discussion seems to go big picture, dive down to case studies, and then back out to a discussion of HLs. This organization seems a bit haphazard and cobbled together. I wonder if better flow and cohesiveness from section to section could be achieved here.

Response) We added a separate subsection for the results and discussion of case studies (Section 4.3). We refined the language of "examples" to case studies throughout the document. This case study section was moved after the latter discussion of HLs for smoother continuity. Also updated the abstract and intro accordingly (L35-36; L138-145; Section 3.2.2; Section 4.3).

18) Specific Comment (Sections 4 and 5: Results and Discussion)

The results section is dominated by description of the climatic time series and changes to the HL indices classifications, but explanation of those changes largely disappear in the discussion and is dominated by discussion of vulnerability. I get that the vulnerability index is an attempt to merge some of those ideas, but I would have expected better mixing of the climate and HL information in with the vulnerability discussion.

Response) *We have further highlighted the integration of climate, the HL classification approach, climate vulnerability, and socio-economic impacts throughout the paper, especially the intro, discussion, and conclusions. (Section 4.2; Section 4.3; Section 5)*

19) Specific Comment (Lines 260-262)

You stated in the methods that you chose from the highest emissions scenarios climate data projections (RCP 8.5). Better admonition of that fact needs to be detailed in the discussion as several other projection scenarios show lower degrees of change or better explanation of why you thought the high-end emissions scenarios were most representative needs to be explained.

Response) We explain in the discussion that RCP 8.5 was selected because it most closely relates to the CO2 emission scenarios experienced to date (Section 2.3.3; Section 4.1).

20) Specific Comment (Other)

I think there could be better discussion as to how having high vulnerability in a single metric could have profound implications in some areas while other areas may only be affected by having high vulnerability across multiple metrics. You get at some of this in the case study approach where certain grape varietals are more impacted by temperature changes say rather than precipitation changes, but I think that could be expressed better throughout including in the discussion of HLs. For instance, a change in seasonality could have profound implications to overall hydrology if that change meant a state transition from snow to rain even with a relatively modest change in temperature. There's a robust literature (especially for the west coast) on the impacts of these projected changes. Maybe some incorporation of overall vulnerability across all these indices is warranted. Surely that's industry or stakeholder specific in what they deem "important" as highlighted in the case studies, but better discussion here may be warranted.

Response) We have added a discussion of single vs. multiple metric vulnerability (Section 4.1).

21) Specific Comment (Section 4: Discussion)

Along those same lines, you dedicate a lot of space both in terms of figures and text towards changes in seasonality (Figure 4-5) and FMI (Figures 2-3). Some discussion on whether you expect those to be the most consequential HL metrics in this region would be useful.

Response) Upon further reflection, we have decided to move these methods and results to the supplemental materials.

Reviewer Comments (submitted as RC1)

1) General Comment

The manuscript, using existing indices and geospatial datasets, proposes a framework/rule-based decision making on the vulnerability of the Western U.S to future climate change. The manuscript is interesting and encompasses significant data management and GIS work. My general comments: Reading the manuscript, I have a feeling that HESS is not really the right journal for this work. Although interesting work, the manuscript seems to be a report/technical memorandum that is turned into a scientific manuscript. I would suggest this work may be better presented in other engineering or water management journals. This is just my recommendation on better presenting the work in its context to the right audience. Following that, it is rather difficult to provide a scientific feedback to this work. My feedback remains mostly on the clarification of presentation.

Response) We are happy to see that the reviewer (RC1) found the manuscript interesting, although, as we describe below, we respectfully disagree with this reviewer's suggestion that this research would be more appropriate for an engineering or water management journal. While the reviewer does provide specific feedback that is helpful for improving the manuscript, this feedback does not seem to justify the recommendation to submit to a different journal. This critique also seems inconsistent with the feedback provided by the other reviewer, as well as the stated goals and scope of HESS) Nevertheless, we do find the specific comments provided by the reviewer to be valuable in helping us improve the manuscript, and we have done our best to address these in our revision.

Response)

2) General Comment

The use of English language is very good. The flow of the manuscript is smooth.

> *Response) Thank you.*

3) General Comment

I am not sure if I really understand the linkage between the hydrological landscape classification and the current manuscript. As the authors mentioned in the introduction, the landscape classification is usually at finer resolution than catchment scale. What the author are doing, is more of clustering or zoning of possible system response to climate change (similar to hydrological modeling approach but with less hydrology as only indices are used). The AU are just a unit where the data is compiled at and this is not really linked to the sub-catchment variability intended landscape classification at catchment level.

> *Response) We have added clarification of this information and process (L121-145; L180).*

4) General Comment

It seems the authors have a decision tree in mind that they use for classification using the input data. I would suggest the author to provide a schematic of their decision or algorithm that provide readers with better understanding of the method. Similarly, there is no visualization of the shapefile/regions used to create the vulnerability map.

> *Response) While this process is not a decision tree, we have created a new figure in attempt to summarize the HL code development, the use of historic and future climate projections to generate figures and the vulnerability maps (Figure 2). In addition, the HL classification specifics are described in the methods: Climate (Section 2.2.1); Seasonality (Section 2.2.2); Subsurface Permeability (Section 2.2.3); Terrain (Section 2.2.4); and Surface Permeability (Section 2.2.5). We further clarify that the vulnerability maps depict the ~24,000 AUs that were classified for each Vulnerability parameter, since it wouldn't be very helpful to create a map that shows that level of detail.*

5) General Comment

I would say the context of vulnerability is missing here. What is it used for? What is the intended motivation behind this vulnerability assessment?

> Response) *The context of vulnerability is woven into the entire manuscript and the abstract. We specifically discuss how vulnerability is used in our assessment in L133-138. We also added some introductory language to the end of the first paragraph (L53-58).*

6) General Comment (Section 3: Results)

The result section is presented very quickly in (few) paragraph(s).

> *Response) We believe this material adequately communicates the results of our study when combined with the tables and figures. The text portion of our results equates to*

1576 / 8125 words (19% of the text of the primary manuscript), which does not include tables or figures that will be placed within the section.

7) General Comment (Section 4: Discussion)

   The discussion is kind of back to front. It is rather wordy. I would say it can be significantly shorter and focused on the interpretation of the results given the aim of this study.

   Response)

   We streamlined the content of the discussion and look for opportunities be more brief, while maintaining clarity. We balanced this comment with those by the other reviewer, who suggested adding a subsection and expanding the discussion. However, we restructured the discussion so that the case studies have been moved to the end, so hopefully that helps address the sense that the Discussion had been presented back to front. The discussion is now 1583/8125 words (19% of the paper (inclusive of Intro through conclusions)).

8) General Comment (Section 5: Conclusions)

   Conclusion session is very vague. I would suggest the authors to come up with few bullet points Conclusions which readers can have as take-home message. Also, the discussion, my pervious comment, can evolve along the line of the conclusion (I mean bullet point conclusions can help discussion significantly).

   Response) We emphasize our intended take home messages in the conclusions (Section 5)

9) General Comment

   My overall suggestion is to change the manuscript into technical note. I would strongly suggest shortening of the manuscript and remove wordy sections (for example, in discussion). Explain the decision tree visually and elaborate that in methodology section. Present the forcing and geospatial data in the decision tree and also visually. I believe major revision is inevitable.

   Response) We respectfully disagree with the reviewer's recommendation to change the manuscript into a technical note; see response to comment #1. We shortened the discussion section (while adding a subsection to it) from 1615 to 1583 words. We have attempted to shorten the overall manuscript (now 8125 words) and have removed sections from the results and pushed those to the supplemental materials. While we do not agree that a decision tree is the proper graphic to summarize our overall process, we have added Fig. 2 to illustrate our overall research process.

Short Comment (submitted as SC1)

1) I noted that you cited my work describing vulnerability of stream temperatures to climate change. This paper by Sulochan Dhungel and others may be as relevant to this study since they looked specifically at hydrologic changes in response to climate change: https://onlinelibrary.wiley.com/doi/abs/10.1002/rra.3029

   Response) Thank you. We have reviewed the paper and now cite it at L76-78.

Journal: Hydrology and Earth System Sciences

Using hydrologic landscape classification and climatic time series to assess hydrologic vulnerability of the Western U.S. to climate

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Abstract. We apply the hydrologic landscapes (HL) concept to assess the hydrologic vulnerability of the western United States (U.S.) to projected climate conditions. Our goal is to understand the potential impacts of hydrologic vulnerability for stakeholder-defined interests across large geographic areas. The basic assumption of the HL approach is that catchments that share similar physical and climatic characteristics are expected to have similar hydrologic characteristics. We use the Hydrologic Landscape vulnerability approach (HLVA) to map the HLVA index (an assessment of climate vulnerability) by integrating the HL approach into a retrospective analysis of historical data to assess variability in future climate projections and hydrology, which includes temperature, precipitation, potential evapotranspiration, snow accumulation, climatic moisture, surplus water, and seasonality of water surplus. Projections that are ~~not within~~beyond two-standard deviations of the historical decadal average contribute to the ~~vulnerability~~ HLVA index for each metric. ~~This~~Separating vulnerability into these seven separate metrics allows stakeholders and/or water resource managers to ~~understand~~have a more specific understanding of the potential impacts of future conditions. ~~In~~We also apply this ~~paper, we present example assessments of hydrologic vulnerability of specific geographic~~approach to examine case studies for particular locations~~ (Sonoma Valley~~. The case studies (Mt. Hood, Willamette Valley, and ~~Mount Hood) that~~Napa-Sonoma Valley) are important to the ski and wine industries ~~to~~and illustrate how our approach might be used by specific stakeholders. The resulting vulnerability maps show that temperature and potential evapotranspiration are consistently projected to have high vulnerability indices for the western U.S. Precipitation vulnerability is not as spatially uniform as temperature. The highest elevation areas with snow are projected to experience significant changes in snow accumulation. The seasonality vulnerability map shows that specific mountainous areas in the West are most prone to changes in seasonality, whereas many transitional terrains are moderately susceptible. This paper illustrates how HL and the ~~HL approach~~HLVA can help assess climatic and hydrologic vulnerability across large spatial scales. By combining the HL concept and ~~climate vulnerability analyses, we provide a planning approach that could allow~~HLVA, resource managers ~~to~~could consider ~~how~~ future climate conditions ~~may impact~~in their decisions about managing important economic and conservation resources.

1 Introduction

A stable and predictable water supply is imperative ~~to~~for food security, ecosystem sustainability, economic stability, and even national security (National Intelligence Council, 2012), ~~especially as it pertains to the global food supply, and~~and is related the threats of increased flooding, droughts, wildfire, and more extreme temperatures (Mancosu et al., 2015; Mekonnen and Hoekstra, 2016). The recognition of the potential socio-ecological threats of climate change on ~~society~~the water supply is a critically important topic, and the development of planning tools that identify vulnerabilities to these systems could help decision-makers assess the ~~risk imposed by projected~~risks of environmental changes~~, such as those~~ imposed by climate~~,~~ as well as other contemporary risks (e.g., population growth~~, or~~ and habitat conversion) (Glick et al., 2011; Lawler et al., 2010). ~~Environmental changes related to climate and hydrology~~Climatic and hydrologic change will not impact stakeholders equally across sectors, thus the specific concerns and adaptation strategies of different industries ~~will vary.~~ threatened by those risks will vary. The hydrologic landscapes vulnerability assessment described herein provides a relatively simple approach for assessing hydrologic vulnerability based upon inferences of hydrologic behavior (using hydrologic landscapes) in response to climatic impacts. This approach can be applied across large geographic regions and can potentially benefit numerous sectors, including environmental, economic, and other ecosystem services.

Numerous studies have examined projected changes in climate and hydrology on regional and national scales that included the western United States (U.S~~.~~.). The ~~Third~~Fourth National Climate Assessment ~~(http://nca2014.globalchange.gov)~~ is a comprehensive resource for climate-related research in the U.S. ~~(Melillo et al., 2014).~~(U.S. Global Change Research Program (USGCRP), 2018). Nolin and Daly (2006) mapped climate-related risk to snow-dominated areas and ski areas in the Pacific Northwest~~.~~ (PNW, which includes Washington, Oregon, and Idaho). Mote et al. (2005) compared the spatial patterns of snow water equivalent observations to model simulations in the western U.S. Brown and Mote (2009) examined projected changes in snow water equivalent globally based on 14 model projections. Barnett et al. (2005) identified potential climate-driven water supply deficits in snow-dominated areas around the globe, although rising water demands have been found to greatly outweigh potential climate impacts on future (year 2025) water supply ~~(Vorosmarty et al., 2000)~~(Vorosmarty et al., 2000). McAfee (2013) examined projected changes in potential evapotranspiration (PET, calculated using numerous methods) ~~between 2002-2011~~ and ~~2079-2098. The findings are consistent across~~found regional analyses to be more inconsistent than studies ~~in many areas of the globe including~~ across the conterminous U.S., ~~but other regional PET predictions were inconsistent and sensitive to the method of calculation~~which indicated sensitivities to the methods used. Hill et al. (2013, 2014) predicted thermal vulnerability of streams and river ecosystems to climate across the U.S., while Battin et al. (2007) found that ~~in regards to~~ salmon habitat~~,~~ in snow-dominated streams ~~were~~was more vulnerable than habitat ~~than~~in lowland streams. The analyses of Nijssen et al. (2001) on hydrologic sensitivity of rivers globally found: 1) ~~Ubiquitous~~ubiquitous warming, with greatest warming in winter months at higher latitudes, 2) ~~More~~more precipitation with high variability, 3) ~~Early~~early to mid-spring snowmelt caused increased spring streamflow peak in coldest basins, decreased spring runoff and increased winter runoff in transitional basins, 4) ~~Tropical or mid-latitude basins had decreased annual runoff, and 5) High latitude basins had increased annual streamflow.~~tropical or mid-latitude basins had decreased annual runoff, and 5) high latitude basins had increased annual streamflow. While snow-fed streams in the western US seem less likely to change flow regimes, perennial and intermittent, rain-fed streams are more likely to change in flow regime (Dhungel et al., 2016). In response to droughts of the recent past, Mann and Gleick (2015) highlight the strong correlation between very hot years and very dry years; thus as temperatures increase at the upper extreme, precipitation is becoming more scarce. A study by Cook et al. (2015) found a growing risk of unprecedented drought in the western U.S. based on temperature projections and no clear pattern in future precipitation.

~~-~~“Vulnerability” has been defined in many ~~accepted definitions~~ways, depending upon discipline and application (Adger, 2006; Füssel, 2007). Vulnerability assessments often integrate exposure, sensitivity, and adaptive capacity to stressors (Adger, 2006; Füssel, 2007; Füssel and Klein, 2006; IPCC, 2014). Researchers have studied vulnerability at varying scales across numerous regions for a diversity of stakeholders, and they tend to focus on the most relevant metrics for their particular application (Farley et al., 2011; Glick et al., 2011; IPCC, 2014; Nolin and Daly, 2006; U.S. Global Change Research Program, 2011; Watson et al., 2013). Yet, better products and services are needed to enable local communities to plan for and respond to hydrologic change, which includes services that improve understanding, observing, forecasting, and warning about significant hydrologic events (Tansel, 2013). Glick et al. (2011) and Lawler et al. (2010) both emphasize the importance to managers of understanding the potential impacts of climate on the resources that they manage.

There have been many efforts to assess hydrologic vulnerability related to specific stakeholders, ecosystems, or locations. For example, Vörösmarty et al. ~~(2000)~~(2000) examined the vulnerability of global water resources to changes in climate and population growth. Hill et al. (2014) assessed stream temperature vulnerability to climate for sites across the U.S. In another example, Winter (2000) suggested that the vulnerability of wetlands to changes in climate depends upon their position within the hydrologic landscape.

There are opportunities to build upon previous efforts to map hydrologic vulnerability across large geographic areas, while creating tools that stakeholders may use to understand the potential impacts for their asset of interest in specific watersheds. Winter (2001) described the concept of classifying the physical landscape and climatic properties of ~~catchments~~large landscape units based on hydrologic landscapes (HL). Surface and ground water availability in watersheds is impacted by differences in geology, terrain, soils, seasonal temperature patterns, precipitation magnitude, and precipitation timing (Tague et al., 2013; Winter, 2001) and are not uniform across regions (Hamlet, 2011; Jung and Chang, 2012; Tague and Grant, 2004). Catchments that share similar key physical and climatic characteristics are expected to have similar hydrologic characteristics; i.e., surface and ground water interactions, deposition, timing, and accumulation of precipitation, surface runoff patterns, and groundwater flow (Nolin, 2011; Thompson and Wallace, 2001).

The HL concept has been applied to the U.S. using a clustering method (Wolock et al., 2004) ~~and~~to develop twenty non-contiguous regions, which were much larger than the catchment scale. Since that effort, modified approaches have ~~been~~not used clustering approaches, but have used catchment-based classification in Oregon (Leibowitz et al., 2014; Patil et al., 2014; Wigington et al., 2013), Nevada (Maurer et al., 2004), the ~~Pacific Northwest~~PNW (Comeleo et al., 2014; Leibowitz et al., 2016), and Bristol Bay, Alaska ~~(Todd et al., 2017).~~(Todd et al., 2017). In applying the HL approach in Oregon and the ~~Pacific Northwest,~~PNW, the clustering approach was abandoned for a conceptual approach based upon important factors known to contribute to hydrologic flow (Wigington et al., 2013), where two climatic factors and three landscape characteristics were categorized for each catchment; the resulting classification allows the ~~prediction~~estimation of catchment-scale hydrologic behavior across large spatial scales. The approach shows promise in predicting seasonal and monthly hydrologic patterns (Leibowitz et al., 2014). Leibowitz et al. (2014) adapted the classification system applied by Wigington et al. (2013) to illustrate the applicability of HLs at the watershed scale for representing normal (1971-2000) monthly average streamflow in three case study watersheds in Oregon. They used climate projections (2041-2070) to estimate hydrologic behavior of ~~catchments~~watersheds relative to 1971-2000. Leibowitz et al. (2016) expanded the approach and applied the HL classification to Oregon, Washington, and Idaho. The more recent studies using the hydrologic landscape classification approach have been applied at a watershed scale (Patil et al. 2014, Leibowitz et al. 2016, Todd et al. 2017).

A number of tactics have been used to investigate the influence of climate on hydrologic behavior (Luce and Holden, 2009; Safeeq et al., 2014; Vano et al., 2015). To extend the work previously completed from HL-based climate projections, we assess ~~climate~~hydrologic vulnerability at the catchment scale by integrating the HL approach into an analysis of climatic variability. Our hydrologic landscape vulnerability ~~analysis~~approach (HLVA) provides spatially continuous, application-specific estimates of climatic vulnerability~~.~~ (maps of the HLVA indices). One of the benefits of the HLVA is to place ~~modern~~recent and projected environmental changes in the context of available historic data. In the HLVA, we use proxies for the three components of vulnerability: a) historic climate data and their derivatives as proxies for sensitivity~~;~~ (the sensitivity of a particular system to each variable); b) climate projections as proxies for exposure~~;~~ (the future projected condition increases or decreases a system's exposure to a change); and c) qualitative considerations of ecosystems, stakeholders, or industries as proxies for adaptive capacity~~. The HLVA assesses~~ (the presence of a system in a location is indicative that the system has historically had sufficient adaptive capacity to exist in that area). Using HLVA, we examine vulnerability to changes in temperature, precipitation, potential evapotranspiration, snow accumulation, surplus water, climatic moisture, ~~surplus water,~~ and seasonality of the water surplus. This method highlights areas that are projected to experience deviations from historic conditions to understand the patterns in magnitude, timing, and type of precipitation and the quantity and seasonality of available water at a catchment scale. These estimates of hydrologic vulnerability could offer important insight into the potential resilience of socially and economically valuable locations and stakeholders in an area.

We ~~apply the HL concept with the goal of assessing~~assess the hydrologic vulnerability of socially and economically valuable locations by applying the HL concept using climatic projections in the western U.S. ~~to magnitude and variability in climate projections.~~ We analyzed ~~this data~~the output from the HL analyses to address three research objectives: 1) develop an index of vulnerability based on ~~past and projected~~ climate ~~behavior~~; 2) map areas that are projected to be more vulnerable to environmental ~~changes associated with climate~~change; and 3) determine the vulnerability indices ~~of seven metrics (temperature, precipitation, snow accumulation, PET, surplus water (S'), Feddema Moisture Index (FMI; Feddema, 2005), and seasonality)~~ for ~~specific geographic areas~~socially and economically valuable locations, including three ~~examples of~~example case studies for regional industries that are economically important in the region. By integrating the concept of hydrologic landscape classification, hydrologic vulnerability, and climatic impacts, this study lays the groundwork for making spatially explicit generalizations about the hydrologic vulnerability of socially and economically valuable locations across large landscapes.

2 Methods

~~1~~2.1 Study Area

The study area includes the states of Washington, Oregon, Idaho, California, Nevada, and Arizona in the western U.S. (Fig. 1). These states extend across a wide range of climates and diverse physiographic settings. The lowest elevation across the six states is 85 m below sea level (Death Valley, California), while the highest elevation is 4421 m above sea level (Mt. Whitney, California) [U.S.G.S. National Elevation Dataset available at:

https://nationalmap.gov/elevation.html]. The Sierra-Nevada Mountains are oriented in a north-south direction near the eastern border of California and transition to the Cascade mountain range that ~~runs in a~~is oriented north~~/~~-south ~~direction~~ through Oregon and Washington~~.~~ (US Topo Quadrangles available at: https://nationalmap.gov/ustopo). ~~However, there~~There are numerous other mountain ranges in ~~each of~~ the other states as well. The Sierra-Nevada and Cascade mountain ranges generate orographic effects that cause upwind areas to the west to have ~~much~~ greater precipitation relative to the downwind, eastern regions (Dettinger et al., 2004; Siler et al., 2013). High elevation areas receive most of their precipitation as snow (Brekke et al., 2009; Mote et al., 2005), while lowland and coastal areas receive ~~their precipitation mostly as~~predominantly rain (Brekke et al., 2009; Mock, 1996), but much of the ~~six-state~~study area receives a balance of snow and rain. The topographic differences ~~across the landscape~~ drive precipitation patterns across the ~~six state study~~ area and cause ~~large~~ differences in the total annual precipitation or the seasonality of maximum precipitation (Mock, 1996). In the arid southwest, summer monsoons deliver most of the annual precipitation ~~(Mock, 1996), whereas in the Pacific Northwest, winter rains and snows are the dominant form of precipitation~~, whereas in the PNW, winter rains and snows prevail (Mock, 1996). However, the western U.S. is regularly affected by atmospheric rivers that deliver large quantities of rain or snow over short periods (Dettinger, 2011; Hidalgo et al., 2009). The seasonal variability of surface air temperature varies widely across the study area. Portions of each state ~~in our study area~~ are classified as deserts with summer maximum temperatures regularly exceeding 40°C ~~(NOAA State Climate Extremes Committee, 2016)~~(NOAA State Climate Extremes Committee, 2016). Each state ~~in the study area~~ has also recorded temperatures less than -40°C ~~(NOAA State Climate Extremes Committee, 2016)~~(NOAA State Climate Extremes Committee, 2016). Some ~~portions of the study area~~areas have ~~very~~ mild climates with little seasonal variation in temperature (Daly, 2016b). ~~Bedrock geology~~Geology in the study area varies from high permeability sedimentary deposits or relatively recent volcanic deposits, to low permeability igneous metamorphic and sedimentary formations and older volcanics (Comeleo et al., 2014; Stratton et al., 2016).

~~1~~2.2 Hydrologic landscape classification

~~The study area was divided into 29,356 assessment~~Assessment units (AUs~~). The AUs~~) are aggregations of NHDPlusV2 catchments (McKay et al., 2012) that were grouped to have a target area of 80 km^2, as described in ~~Wigington et al. (2013) and modified by Leibowitz et al.~~Leibowitz et al. (2016). In this study, the same assessment units used in Leibowitz et al. 2016 study have been used and their method applied to the expanded six state study region to delineate 29,097 assessment units for the study's expanded 6 state study region. For this analysis, we retain an AU if its centroid was located within the boundary of our project area or if the AU extended across an international boundary. All AU polygons are ~~also~~ clipped to the international boundary of the U.S. These conditions allow us to avoid edge effects at international and state borders by avoiding overlapping AUs at state boundaries and analyzing the HLs up to all international borders. ~~The project boundary was defined by merging these AUs into a single polygon.~~

Building upon Winter's (2001) approach and the Wolock et al. (2004) clustering approach, Wigington et al. (2013) developed their simple conceptual HL classification based on climatic and physical characteristics of the physical watershed. They ~~defined~~combined five indices related to hydrologic flow (Fig. 2a) to characterize the major drivers that control the magnitude and timing of water movement through the landscape and into the ~~ground~~groundwater or stream network: (1) climate, which describes the overall water availability~~ of water on the landscape~~, (2) seasonality of water surplus, which is the season when the maximum excess of water is available to infiltrate into the soil ~~column~~ or flow as surficial runoff, (3) subsurface permeability, (4) terrain, and (5) surface permeability. Note that Wigington et al. (2013) referred to subsurface and surface permeability as aquifer and soil permeability, respectively. The five HL indices, described in more detail below (Sections ~~1.~~2.2.1- through ~~1~~2.2.5), are ~~typically~~ concatenated into a 5-character HL code (e.g., WsLMH, SwHTH, or DfHfL) that characterizes an AU.

Leibowitz et al. (2016) ~~developed an HL map of the Pacific Northwest (PNW, consisting of Oregon, Idaho, and Washington) based on a modification of the~~ modified the Wigington et al. ~~(2013)~~(2013) approach by including: the use of assessment units based on National Hydrography Dataset Plus V2 catchments, a modified snowmelt model that was validated over a broader area, a subsurface permeability index that does not require pre-existing aquifer permeability maps, and a surface permeability threshold based on objective criteria. Using this modified method (herein described as the modified Wigington et al. (2013) approach~~). For the current effort~~), they developed an HL map of the PNW. Here, we used the modified Wigington et al. (2013) approach to develop an HL classification of California, Nevada, and Arizona~~ [referred to as the southwest]~~. This was then combined with the PNW map (Leibowitz et al., 2016) to create an HL map of the ~~six western states~~study area.

~~1~~2.2.1 Climate

The Wigington et al. (2013) approach derived the climate index from the Feddema Moisture Index (FMI) (Feddema, 2005):

$$FMI = \begin{cases} 1 - \frac{PET}{P} & if\ P \geq PET \\ \frac{P}{PET} - 1 & if\ P < PET \end{cases} \qquad (1)$$

where FMI (Eq. (1)) values range from -1.0 (arid) to 1.0 (very wet). P is the mean precipitation (mm) over a 30-year ~~normal~~period, which is derived from climate data described in Section ~~0,~~2.3, and PET is the potential evapotranspiration (mm) calculated using the Hamon (1961) method, that utilizes mean daily temperature, daytime length (calculated based on latitude), and a calibration coefficient. The range of FMI values was the basis for defining a climate index consisting of six classes: arid (A; -1.0 ≤ FMI < -0.66), semiarid (S; -0.66 ≤ FMI < -0.33), dry (D; -0.33 ≤ FMI < 0.0), moist (M; 0.0 ≤ FMI < 0.33), wet (W; 0.33 ≤ FMI < 0.66), and very wet (V; 0.66 ≤ FMI < 1.0) ~~(Wigington et al., 2013)~~(Wigington et al., 2013). FMI was calculated from regional precipitation rasters (described in Section ~~0)~~2.3) for each period of interest. The FMI value was then averaged over each AU.

~~1~~2.2.2 Seasonality

We used the Leibowitz et al. (2016) approach to develop a seasonality index that identifies the season of the maximum monthly average snowpack-corrected surplus water (S'_m):

$$S'_m = S_m - \Delta PACK^*_m$$

~~$= (P_m - PET_m)$~~

$$S'_m = (P_m - PET_m) - (PACK^*_m - PACK^*_{m-1}) \qquad (2)$$

where S'$_m$ (Eq. (2)) is the average snowpack-corrected water surplus (mm) for month *m*, S$_m$ is monthly water surplus (P - PET), and P$_m$ and PET$_m$ are monthly precipitation and monthly PET, respectively. PACK$_m^*$ is a monthly bias-corrected snowpack value (in mm of snow water equivalent, or SWE) restricted to values greater than zero, based on the Leibowitz et al. (2016) modifications to the Leibowitz et al. (2012) snowpack model. Note~~, however,~~ that $\Delta PACK^*_m$ can have negative values, which represents snow melt. For each month, S'$_m$ was calculated for the regional raster~~ for each month~~, before identifying the month of maximum S'$_m$ for the majority of pixels in each AU. The month of maximum S'$_m$ was used to identify the season of maximum S'$_m$ based upon four seasonality classes: fall (f; October−December), winter (w; January−March), spring (s; April−June), and summer (u; July−September). The PNW analysis by Leibowitz et al. (2016) only included two seasonality classes; summer seasonality did not occur~~ and~~, while fall and winter were combined into a winter class, since this represented the PNW's wet season. For ~~our~~this analysis, ~~we kept~~ winter and fall ~~separate~~were separated and ~~used~~ all four seasonality classes were used, because fall and winter are distinct seasons in other parts of the nation.

~~1~~2.2.3 Subsurface permeability

Leibowitz et al. (2016) utilized the Comeleo (2014) aquifer permeability dataset. We applied a similar approach ~~from~~to the Stratton et al. (2016) aquifer permeability datasets, which is herein referred to as subsurface permeability. Each ~~of these datasets classify~~dataset classifies the subsurface permeability into high (H) and low permeability (L) classes, which are assigned with a threshold ~~guideline~~ of 8.5 x 10^{-2} m day^{-1} hydraulic conductivity. Using these data, we analyzed the subsurface permeability of each AU by identifying the subsurface permeability class for the majority of pixels within each AU in ~~the three south western states~~California, Nevada, and Arizona.

~~1~~2.2.4 Terrain

To classify terrain, we used the same approach as Wigington et al. (2013). We analyzed a 30 m Digital Elevation Model to classify the landscape based upon the topographic characteristics of each AU. "Mountainous" (M) areas had AUs with <10 % of the area identified as flat (< 1 % slope) and greater than 300 m of total relief. AUs with more than 50 % area having < 1 % slope were classified as "flat" (F). All other AUs were identified as "transitional" (T).

~~1~~2.2.5 Surface permeability

For surface permeability, the ~~Wigington~~Leibowitz et al. (~~2013~~2016) HL approach utilized the STATSGO soil permeability raster developed by Pennsylvania State University Center for Environmental Informatics (www.cei.psu.edu) for the top 10 cm of soil (Miller and White, 1998) in the conterminous U.S. The STATSGO soils database was selected because of its complete coverage of the conterminous U.S., despite SSURGO's higher spatial resolution, ~~which did not have complete spatial~~yet incomplete coverage of the ~~U.S. They~~study area. Leibowitz et al. (2016) identified whether the majority of each AU had high (H; >1.52 cm/hr) or low (L; ≤ 1.52 cm h^{-1}) soil permeability. We applied the same approach to classify surface permeability of each AU into two classes throughout the region.

~~1~~2.3 Climate analyses

~~1~~2.3.1 ~~Modern~~Climate normal (1971−2000)

The climate normal ~~**(1971−2000)**~~ was defined as the 1971-2000 period to align with the Leibowitz et al. (2016) study. Average monthly precipitation and mean temperature were acquired from Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly, 2016b) data for our normal climatic period at a resolution of approximately 400 m. The PRISM Climate Mapping Program is an ongoing effort to produce detailed, spatial climate datasets (Daly, 2016a; Daly et al., 2000). PRISM uses point measurements of climate data and a digital elevation model to map climate across the U.S. from 1895−present, including regions impacted by high mountains, rain shadows, temperature inversions, coastal regions, and associated complex meso-scale climate processes. Using ArcGIS (ESRI, 2016), the data were clipped to the project boundary and used to calculate the average for ~~our~~ seven metrics~~ (~~: monthly temperature~~,~~ (°C), precipitation~~,~~ (mm), PET~~,~~ (mm), surplus water~~,~~ (mm), snow water equivalent~~,~~ (mm), the FMI~~,~~ climate index~~,~~ (unitless), and seasonality of water surplus~~) for the normal period.~~ (unitless). Each ~~of these metrics are inputs~~metric is an input to or products of the HL classification process.

~~1~~2.3.2 Historical climate analyses (1901−2010)

Unlike ~~with~~the 1971-2000 monthly precipitation and temperature data, a time series of gridded ~~daily~~monthly historical climate data at a spatial resolution of 400 m was not available~~. Daily~~ without paying a fee. However, daily PRISM data ~~is~~were freely available at 4 km resolution, ~~and this was what~~so we used these to develop the historical climate analyses for the 1901−2010 period. ~~Gridded~~These gridded data for daily mean temperature and precipitation were clipped to the project boundary and averaged for each month over each decade (i.e., 1901−1910, 1911−1920, etc.). The data were then statistically downscaled to 400 m using the delta method (Hijmans et al., 2005; Ramirez-Villegas and Jarvis, 2010) to match the spatial and temporal resolution of the~~ modern~~ climate normal data (using the 400 m resolution, monthly PRISM climate normal for 1971−2000 period as the high resolution dataset). We acknowledge the inaccuracies and uncertainty imposed in the temperature and precipitation datasets by applying the downscaling functions to the original climate projections~~, however since these 400 m resolution monthly averages are normally distributed (Trzaska and Schnarr, 2014) and the data are to be aggregated to our 80 km^2 (on average) AUs, the tradeoffs~~. While the 400m data clearly have greater resolution and less error than the 4km data, these data were to be aggregated to assessment units with a mean area of 56 km^2. In practice, the larger 4km resolution of the downscaled historical analysis should still be appropriate for the scale of the assessment units, thus the trade-offs were deemed acceptable and preferable for characterizing the hydrology and climate for these analyses~~.~~ with no additional budget requirements.

~~Using~~Based on the approaches described~~ herein~~, the downscaled data were used to calculate the average monthly PET, surplus water, snow water equivalent, FMI, and seasonality of water surplus for each decade~~.~~ (Fig. 2b). Summary figures were generated from this data depicting spatial distribution of climate and seasonality for each decade across the project area. These data were compared to the ~~modern~~ climate normals using spatially continuous time series analyses (Fig. S1).~~.~~

~~1~~2.3.3 Future climate analyses (2041−2070)

In order to explore the potential range of modeled climatic response for the study area, we selected ten climate model projections from the full ensemble of World Climate Research Programme's Coupled Model Intercomparison Project phase 5 multi-model ensemble climate dataset projections (WCRP CMIP5; http://cmip-pcmdi.llnl.gov/cmip5; Taylor et al., 2012). ~~These models are based on the Representative Concentration Pathway (RCP) 8.5 emissions scenario, which assumes the highest rate of emissions into the 21st century. We only used this emissions scenario to reduce the complexity of the analyses. To select the specific model simulations to use in this study, we created~~These models are based on the Representative Concentration Pathway (RCP) 8.5 emissions scenario, which assumes the highest rate of emissions into the 21st century and most closely relates to conditions observed to date (Schwalm et al., 2020). To reduce the complexity of the analyses, we used only this one emissions scenario. To select the specific model simulations to use in this study, we used the U.S. Environmental Protection Agency's (EPA) LASSO tool (lasso.epa.gov; U.S. EPA, 2020) to generate a scatterplot comparing future temperature and precipitation change for the different CMIP5 models over the project area. ~~We~~Using the scatterplot and the approach described by U.S. EPA (2020), we subjectively selected ten models that spanned the entire range of predicted climatic responses of the full ensemble in a distributed manner (Fig. ~~2~~3), including drier, wetter, colder, and warmer responses. Average monthly precipitation and temperature for the ten projections (Table 1) were acquired from the monthly Bias-Correction and Spatial Disaggregation (BCSD) archive (Bureau of Reclamation, 2014) for the 2041−2070 period. These data were clipped to the project boundary and resampled to a 400 m grid using a bilinear approach (ESRI ArcGIS v10.4) to match the resolution and spatial extent of the ~~modern~~ climate ~~normal~~ data. The average monthly PET, surplus water, snow water equivalent, FMI, and seasonality of water surplus were calculated from the future climate data for each assessment unit. ~~Summary~~Example figures were generated that illustrate the spatial distribution of ~~climate and seasonality for each climate projection. The~~the differences in FMI (Fig. S1 and S2) and seasonality of water surplus (Fig. S3 and S4) from the normal period ~~were also mapped and compared.~~for each climate projection (Fig. 2c).

~~1~~2.4 Mapping vulnerability indices

As discussed in the introduction~~ (Section 1),~~, vulnerability can be measured by assessing the *exposure*, *sensitivity*, and *adaptive capacity* of a system to change (Adger, 2006; Füssel, 2007; Füssel and Klein, 2006; IPCC, 2014). ~~Historic hydrology~~Hydrology and climate are primary ~~drivers~~forcing factors for ~~ecosystem change~~ecosystems (Nelson, 2005)~~,~~ and are critical to certain industries and stakeholders in particular areas~~;~~, and thus analyses of historic variation in hydrology and climate in an area can serve as proxies for the historical *sensitivity* of those systems to environmental change. ~~In the assessment of hydrologic vulnerability, we evaluated the variability in historical climate data and our derived hydrologic metrics as a proxy for sensitivity.~~ Likewise, we used future climate projections as a proxy for *exposure*~~ to environmental change.~~. Projections that fell outside of historic observations ~~should then~~ were assumed to be associated with increased ~~levels of~~ exposure to the forcing factors for environmental change, which include hydrology and climate. In terms of *adaptive capacity*, we assumed that the systems present in a location are adapted to the historic ~~observed~~ variability in conditions. We also assumed that the systems would become stressed by conditions far outside of those previously experienced. Further, we suggest that the ~~larger~~greater the number of future climate projections that exceed or fall far below ~~their~~the historic range, the more vulnerable a system ~~associated with a particular climate~~ will be with respect to climate-induced changes. ~~Our hydrologic landscape vulnerability analysis~~ ~~(~~Thus, HLVA~~)~~ places ~~modern and~~ projected environmental changes in the context of ~~available~~ historic ~~data~~trends. The HLVA assesses vulnerability to changes in temperature, precipitation, potential evapotranspiration, surplus water, snow accumulation, climatic moisture, ~~surplus water,~~ and seasonality of the water surplus by identifying areas that are projected to experience future deviations from historic conditions~~.~~ (Fig. 2e).

The ten future climate projections (for the 2041−2070 period) were compared to the decadal averaged data from 1901−2010 for each AU. We calculated the historical standard deviation of each metric for each AU within the project area. For each metric, we assume that any projection ~~that is~~ within two-standard deviations of the historical climate values does not contribute to an increase in vulnerability, whereas projections outside of that range increase the vulnerability. We then define vulnerability for a given ~~index~~metric as the number of the ten projections that are outside of the historical two-standard deviation threshold. Thus, the HLVA index assesses the likelihood that a given metric will exceed a two-standard deviation threshold from the decadal mean under future climate scenarios. Because individual models exceed the threshold of two standard deviations from the mean in both the higher and lower directions, there is not a unique direction of change associated with the vulnerability index. Thus, the vulnerability index, as defined, does not convey information about projected direction of change. A vulnerability index of ten indicates that all ~~of the~~ ten climate projections were beyond two-standard deviations from the historical mean and ~~so are~~that the area is expected to experience projected conditions that ~~they are~~it is not adapted to. The least vulnerable areas will have an index of zero, which indicates that all ~~of the~~ future climate projections fell within the two-standard deviation threshold to which systems are adapted to. The use of standard deviations is not an appropriate threshold metric for seasonality, because it is a categorical variable. For the seasonality metric, any projected seasonality value that has not been observed decadally between 1900 and 2010 increases the seasonality vulnerability index. For example, consider an AU that had predominantly experienced ~~Spring~~spring seasonality, with the occasional ~~Fall~~fall seasonality, and that 7 of 10 climate models project ~~Fall~~fall seasonality and 3 of 10 models predict ~~Winter~~winter seasonality for 2041−2070. Since ~~Winter~~winter seasonality was not observed for any decade between 1900 and 2010, the three predictions for ~~Winter~~winter seasonality ~~each~~would contribute to ~~the~~a vulnerability index of three for seasonality in that case. Finally, we analyzed the dominant HL code by area of the most vulnerable AUs (those having a vulnerability index greater than seven on a scale of ten) for each metric in order to gain insight about the dominant HL characteristics that relate to hydrologic vulnerability.

~~1~~2.5 Locational time series analyses

Forty-five locations (Fig. 1 and Table 2) were selected for potential applications of the HL approach~~, based in part~~ to demonstrate the method's relevance to potential water resource stakeholders to identify areas where we thought results could be of use to land managers. ~~The time series for the decadal averages for each of the seven HL metrics were analyzed for the AUs associated with each of these locations.~~Specific sites were selected subjectively so that we could examine representative climate impacts at sites that may be of general interest. These sites include cities, national parks, mountains, national forests, and areas with hydrologically sensitive economic interests. AUs were used to represent a geographic feature if its centroid was located within the geographic boundary of a location of interest. The location boundary was defined by merging these AUs into a single polygon. For instance, the Great Basin National Park (GBNP) was covered by a single AU, rather than numerous AUs because the centroid of only one AU was within the park boundary, whereas all other AU centroids were located outside of the GBNP boundary. The time series for the decadal averages for each of the climate-related HL metrics were analyzed for the AUs associated with each location. Decadal averages were plotted at the decadal midpoint for each 10-year period from 1901 to 2010. In addition, the 1971−2000 normal average for each variable and ten climate projections (2041−2070) were also plotted ~~in a similar manner~~. The HLVA was then used to determine the mean vulnerability index and the dominant HL code for the AUs associated with each location~~.~~ (Fig. 2d).

~~2~~3 Results

~~2~~3.1 Hydrologic landscape summary

~~Table 3~~Table 3 shows the percent coverage of the HL categories for the six states. Thirty percent of the region is mountainous (elevation relief of AU > 300 m and < 10 % of AU area has slope < 1 %) and 7 % is flat (AUs with more than 50 % area having < 1 % slope). The remaining area is classified as transitional. According to the soil permeability dataset (Miller and White, 1998) produced from the STATSGO soils database (Soil Survey Staff, 2016), 98 % of the surface soils (defined as the top 10 cm) are highly permeable (> 4.23 µm s^{-1}). Stratton et al. (2016) and Comeleo et al. (2014) classified the subsurface permeability of the six-state region as 60 % high permeability and 40 % low permeability. ~~In terms of~~During the 1971−2000 climate normal period, most of the area has the highest monthly water availability (seasonality) during the winter (63 %), followed by 24 % of the area showing fall ~~(24 %),~~seasonality, 13 % having spring ~~(13 %),~~seasonality, with ~~approximately~~only 1 % experiencing summer seasonality. In addition, 30 % of the area is classified as having a moist, wet, or very wet climate, while 70 % is dry, semi-arid or arid. The HL maps for the study area ~~(Washington, Oregon, Idaho, California, Nevada, and Arizona)~~ are included in the appendix (Fig. A1~~(a-ebulnera~~). HL maps for the remainder of the conterminous ~~US~~U.S. are also available and are ~~also~~ included as supplemental material (Fig. S6; although~~S1). Note that the~~ subsurface permeability maps ~~were~~are not ~~extended across~~available for all of the lower 48 states~~ prior to submission, yet are also available as supplemental material.~~).

~~2~~3.2 Climate ~~analyses~~

~~2.2.1 Regional (spatially continuous) time series analyses~~

~~Figure 3 contains spatial trends in the change in FMI for the western U.S., showing wetter or drier decades relative to the 1971−2000 baseline period (Figure S2 in the supplemental material illustrates similar data for the continental US).~~

~~Figure 4 displays projections of future (2041–2070) FMI values for the western U.S. relative to the 1971-2000 normal period, based on the ten climate projections (Figure S3 in the supplemental material illustrates similar data for the continental US). Three of the climate models (CCSM-R4, MRI-CGCM3, and CESM1) indicate that portions of the western U.S. may be wetter (as indicated by the blue areas in Fig. 4), while other areas will be drier (red) than or similar to the 1971–2000 normal. Similarly, the maps suggest that seven of the climate models (CCSM4, GFDL, inmcm4, CanESM2, HadGEM, CSIRO, and MIROC) project that much of the western U.S. will be considerably drier than the normal period. The remaining models indicate that some areas will be slightly drier, whereas much of the area will be similar to the 1971–2000 normal condition.~~

~~Figure 5 illustrates where the seasonal classes of surplus water have varied between 1901 and 2010 relative to the 1971–2000 base period (Figure S4 in the supplemental material illustrates similar data for the continental US). Most areas throughout this historical period show little variation in the season of maximum available water (i.e., are shown in white), but there are patterns in the water surplus seasonality that can be observed in the West. The 1940s, 1960s, 1980s, and 2000s seem to show later seasonality in southern Oregon and Idaho and Northern California and Nevada. In contrast, portions of Oregon, Washington, and Arizona are shown to have earlier seasonality in the 1900s, 1910s, 1930s, 1950s, and 1970s.~~

~~Figure 6 illustrates the seasonal changes in surplus water as projected by the ten climate models for 2041–2070 compared to 1971–2000 (Figure S5 in the supplemental material illustrates similar data for the continental US). In general, most of the climate models predict earlier surplus water in many of mountainous areas in the six western states. Although most mountainous areas in Nevada are projected to have little change in seasonality, those that are projected to change are projected to have earlier seasonality. In Arizona, the White Mountains are predicted to have a later seasonality in two of ten climate projections (MIROC and GFDL), whereas seven projections predict earlier seasonality in western Arizona.~~

~~2.2.2~~ Vulnerability analyses

~~The vulnerability maps (Fig. 7~~Using the analyses of historic and future climate, the vulnerability indices were mapped for all seven metrics (examples are provided for FMI and seasonality in the supplemental materials). The vulnerability maps (Fig. 4) identify areas that are ~~more or less~~ subject to extreme future climatic and hydrologic variability (~~Similar~~similar vulnerability maps for the ~~continental US~~conterminous U.S. are included in the supplemental materials (Fig. S6)). Note that while it is possible to evaluate direction of change (greater or less than two standard deviations) for the projection of an individual climate model, the vulnerability index is the integration of ten individual models. Therefore, it is possible for individual models to exceed the threshold of two standard deviations from the mean in either the higher or lower directions; thus there is not a unique direction of change associated with our vulnerability index as it has been defined.

All climate projections indicate that temperature will change almost ubiquitously across the Pacific west, ~~however~~indicating uniformly high vulnerability. However, changes in precipitation are much more spatially variable. The cold deserts and Mediterranean California Ecoregions (~~Level 2)~~Ecoregion level 2) have higher vulnerability, i.e., are more consistently projected to experience changes in precipitation than has been observed since 1901 on a decadal basis. In contrast, major portions of Arizona, Washington, Oregon, and California have areas with low vulnerability to change with respect to precipitation. ~~The~~The PET vulnerability map is similar to the temperature vulnerability map, which is not surprising since the Hamon (1961) method of calculating monthly PET uses temperature as the major input~~, so it is not surprising that the PET vulnerability map is similar to the temperature vulnerability map.~~. The April 1 snow accumulation (snow water equivalent) vulnerability map shows high vulnerability in many mountainous areas throughout the west. This seems to indicate that snow accumulation will change~~ in many mountainous areas throughout the west, but~~, particularly in ~~the~~ transitional areas~~ when~~, compared to the most snow prone areas of the West. S' is a measure of available water (excess water available for soil infiltration or overland flow). The map for S' suggests that the Warm Desert and Marine West Coast Forest Ecoregions are more likely to experience substantial changes in available water (i.e., high vulnerability) in the future. The FMI is calculated from the ratio of PET and precipitation per Eq. (1). The FMI vulnerability map indicates that the ~~Cold Desert Ecoregions of central, Western Washington, the Warm Deserts of Southern California, and High Elevation Sierra Madre Mountains of south eastern Arizona~~Level 2 western Cordillera Ecoregion through northern Idaho (Fig. 1), a band of western Cordillera running north and south through west of central Washington and Oregon (which includes portions of the Cascade Range), and portions of the cold desert ecoregions in southeastern Washington and northwestern Arizona (Fig. 1) are more likely to see substantial changes to the FMI. The regional time series analyses (below) provide more information about whether those areas are expected to become wetter or drier. The seasonality vulnerability map identifies AUs that are likely to have changes in seasonality. Portions of the western Cordillera Ecoregion (Fig. 1; which includes the Sierra-Nevada Mountains in California, the Cascade Mountains in Washington and ~~the Cascades in~~ Oregon, and ~~mountainous areas~~transitional terrain in Idaho) are projected to be more vulnerable to changes in seasonality. ~~All other areas~~Otherwise, large portions of the study area are not projected to be vulnerable to changes for seasonality.

3.2.~~2.3 Study area as a~~1 Vulnerability of hydrologic ~~landscape~~landscapes

~~Table 4~~Table 4 summarizes an analysis of the HL classifications of the most vulnerable AUs for each metric. For example, 75 % of the AUs identified as vulnerable for snow accumulation were classified as dry, moist, or wet, therefore very wet, semi-arid, and arid AUs are less likely to be vulnerable to changes in snow accumulation. Likewise, 76 % of AUs vulnerable to changes in seasonality had a spring seasonality during the 1971−2000 normal period. The physical properties represented by the dominant HL classes in Table 4 could help determine how various climate vulnerabilities are ultimately expressed. For example, vulnerability to changes in snow or FMI mostly occur in regions with wetter climates (Moist, Wet, or Very Wet climate), with fall or spring Seasonality, in areas with low subsurface permeability. This could result in increased precipitation, with quicker runoff in areas that currently have delayed release of water. Similarly, areas vulnerable to changes in surface runoff are arid landscapes with winter seasonality and highly permeable subsurface parent materials. This means that these changes in runoff could have a large impact on subsurface recharge and, ultimately, baseflow.

3.2.2~~.4 Locational~~ Case studies & locational time series

~~Historic and future changes in ecologically relevant variables are shown for three example locations (Napa-Sonoma Valley, Willamette Valley, Mt. Hood; Fig. 8). Similar~~ Hydrologic vulnerability analyses have been performed for a total of 45 exposure areas of ecological, economic, or social significance ~~(Table 2~~(Fig. 1 and Table 2; see Appendix A (Fig. A2)).~~ The number in the lower left corner of each graph in Fig. 8 indicates the vulnerability index for the specific metric and location.~~ The vulnerability index for each location is also listed in Table 2 for each metric. ~~For instance, precipitation at Mt.~~Three case study locations that are of economic interest are explored in detail and include Mt. Hood (Site #7), Willamette Valley (Site #9), Napa-Sonoma Valley (Site #28). During the normal period, 61 % of the 1867 km^2 Napa-Sonoma Valley~~ Hood has a vulnerability index of '3', which indicates that three of the climate projections exceed the threshold of two-standard deviations from the historic mean. Table 2 indicates that 81 % of the 834 km^2 area analyzed for Mt. Hood (Site #7) had an HL code of VsHMH, (very wet climate with spring seasonality, high subsurface permeability, mountainous terrain, and high surface permeability). During the normal period, sixty-one percent of the 1867 km^2 Napa-Sonoma Valley (Site #26)~~ had an MwHMH HL classification, thus much of the area was classified as having a moist climate with winter seasonality, high subsurface permeability, mountain terrain, and high surface permeability. Eighty-three percent of the 1234 km^2 Willamette Valley AUs ~~(Site #8)~~ had an HL code of WfHTH during the normal period. Overall, the Willamette Valley had a wet climate, dominated by fall seasonality, high subsurface permeability, transitional terrain, and high surface permeability. Table 2 indicates that 81 % of the 834 km^2 area analyzed for Mt. Hood had an HL code of VsHMH (very wet climate with spring seasonality, high subsurface permeability, mountainous terrain, and high surface permeability).

Figure 5 depicts line graphs of the historic and projected changes for the three case study locations (Mt. Hood (Site #7), Willamette Valley (Site #9), Napa-Sonoma Valley (Site #28)). The number in the lower left corner of each graph in Fig. 5 indicates the vulnerability index for the specific metric and location. For instance, precipitation at Mt. Hood has a vulnerability index of '3', which indicates that three of the climate projections exceed the threshold of two-standard deviations from the historic mean.

The time series in Fig. ~~8~~5 (and Fig. A2) illustrate the trend in average decadal temperature, precipitation, SWE, PET, S', climate, and seasonality of water surplus. Note that each future (2041−2070) climate projection ~~represents~~is represented by a single data point that ~~represents~~characterizes the 2041 – 2070 30-year range and is connected in Fig. 5 to the 2001−2010 decade with a dotted red line. Additional figures for ~~41~~42 other locations are provided in Appendix A (Fig. A2). Each of the three example ~~areas~~case studies is predicted to be warmer in the 2041−2070 future climate projections. Further, these projected temperatures are almost always outside of the historic (1901−2010) temperature range, and so all locations have high vulnerability with respect to future temperatures. None of the three ~~examples~~case studies show a strong trend relating to future precipitation projections. Mt. Hood appears to ~~show~~exhibit increasing precipitation since 1901, but there is no evidence that the projected increases in precipitation are outside of historic behavior~~.~~, and so the site has low vulnerability for that metric. Napa-Sonoma and the Willamette Valley have low vulnerability for change in snow, while Mt. Hood has high vulnerability for ~~less~~ April 1 snow ~~accumulation~~water equivalent in the 2041−2070 period. PET is calculated directly from temperature and ~~therefore shows trends~~so its vulnerability is strongly correlated to temperature. There are no obvious trends in S' for the future projections ~~for~~in the ~~selected examples~~three case studies; vulnerability of these sites for S' is low to moderate. The FMI projections for Napa-Sonoma Valley, the Willamette Valley, and Mt. Hood are outside of two-standard deviations of historical trends in three to four out of ten of the projections (~~Table 2).~~Table 2). In terms of seasonality, the vulnerability index is equal to zero in the Willamette and Napa-Sonoma Valleys. For Mt. Hood, vulnerability is low, with all of the future climate projections indicating that there will no longer be spring seasonality (the predominant historical season for runoff~~), but only 3 projections~~). Only three climate models suggest that decadal seasonality would transition to ~~a~~ winter seasonality~~ that is~~, which has not ~~modeled to have~~ occurred since at least ~~1900 on a decadal scale~~1901.

~~3~~4 Discussion

~~Vulnerability maps (Fig. 7) were developed that indicate what areas across the landscape are projected to experience conditions that exceed two standard deviations of the historic decadal average conditions. These maps provide spatially explicit details about the areas of the landscape that are most likely to experience conditions outside of those observed previously for seven different climate indicators. These maps were developed to facilitate long-term planning for stakeholders to be able to assess their risk to climatic impacts. It is possible that ecosystems, businesses, and communities in areas mapped as vulnerable may not be able to adapt to the stresses imposed by future environmental conditions.~~

~~From the vulnerability maps (Fig. 7), it is apparent that temperature [similar to Nijssen et al.~~

4.1 Analyses of Retrospective and Projected Climate and Hydrologic Vulnerability

Vulnerability maps (Fig. 4) were developed to facilitate long-term planning for stakeholders for assessing their risk to climatic impacts. It is possible that ecosystems, businesses, and communities in areas mapped as vulnerable may struggle to adapt to stresses imposed by future environmental conditions. As mentioned previously, the vulnerability index offers no information about the directions of change projected by the ten different models. Further, the RCP 8.5 pathway was selected because it most closely resembles observed conditions (Schwalm et al., 2020).

The consistently projected high temperature vulnerability could lead to problems related to heat stress (e.g., human-related physical and mental health issues), urban heat islands (particularly in areas with little tree cover), and other temperature related problems ~~(2001)] and PET are consistently projected to exceed the two-standard deviation threshold of historic conditions for most regions, though changes in PET may be overestimated (Johnson et al., 2012; U.S. Environmental Protection Agency, 2013). Precipitation vulnerability maps are not as spatially uniform as temperature.~~(USGCRP, 2018). PET vulnerability would be problematic for agricultural systems, forest disease, and sectors that are drought sensitive (USGCRP, 2018). Precipitation vulnerability maps are important in specific areas with regards to flooding, landslides, and drought sensitivities. The vulnerability maps for snow accumulation and S' (surplus water available for runoff or infiltration) show that the areas mapped as most vulnerable for the two metrics are almost reversed, other than central Idaho and the coastal areas of California, Oregon, and Washington. According to the snow vulnerability map, it appears that most areas that receive ~~much~~large amounts of snow are projected to experience significant changes in future snow accumulation. In a related study on snow cover, Nolin and Daly (2006) found that the areas with the warmest winter temperatures are most at risk of having no snow cover in the future. ~~Regarding~~Areas vulnerable for snow could impact not only the ~~Feddema Moisture Index, Fig. 7 suggests that most~~ski industry, but also water supply and streamflows, while the surplus water availability (S') vulnerability metric relates more directly to streamflow and flooding. Most of the ~~models indicate that the magnitude~~study area is not vulnerable to changes in FMI (Fig. 4), which is an assessment of overall water availability, although some areas are (the ~~FMI change is mostly within two standard deviations~~Willamette Valley in Oregon, east of ~~normal.~~Puget Sound in Washington, and the northern panhandle in Idaho appear to be more vulnerable). The ~~seasonality~~ vulnerability map for seasonality (Fig. ~~7~~4) shows that portions of the Western Cordillera (Fig. 1) including the high Sierra-Nevada mountains in California, the Cascade mountains in Oregon and Washington, and the mountainous areas in Idaho ~~are somewhat prone to changes in seasonality.~~), have higher vulnerability indices, which indicates susceptibility regarding water supply, flooding, and streamflows.

~~We used a retrospective analysis of PRISM climatic time series data to gain an understanding of the distribution of environmental conditions present since 1901. While others have mapped resource and hydrologic vulnerability (Hill et al., 2014; Nolin and Daly, 2006; Vorosmarty et al., 2000; Winter, 2000), we are aware of few that have used retrospective analyses to inform the mapping efforts (Deviney et al., 2006; Kim et al., 2011; O'Brien et al., 2004) and are not aware of studies that have mapped resource vulnerability at a large scale using these types of data. It is important to emphasize that our definition of vulnerability is based on agreement of models with respect to climate conditions that are outside of historic ranges. The inference is that systems dependent on historic climate conditions may not be adapted to future conditions, and so are vulnerable. It is possible that they have the adaptive capacity to maintain their ecological and economic systems, but this is not a certainty. The vulnerability maps do not show, however, watersheds or communities downstream of these source areas that would be impacted by these changes.~~

Our retrospective analysis of PRISM time series data provided an understanding of environmental conditions since 1901. We are aware of few that have used retrospective analyses to inform their mapping efforts (Deviney et al., 2006;

Kim et al., 2011; O'Brien et al., 2004), but are not aware of studies that have mapped resource vulnerability at a large scale using such data. Our definition of vulnerability is based on agreement of climate models leading to conditions that are outside of historic ranges. Our hypothesis is that systems having future climate conditions outside of the historic range will not have the capacity to adapt to future conditions, and therefore are vulnerable. The vulnerability issue is complicated by the fact that these vulnerability maps (Fig. 4) do not show how downstream areas could be impacted by these changes.

These vulnerability factors may be of interest to resource managers and decision makers, some of who might consider high vulnerability for a single metric to be problematic. Yet for others, the additive or multiplicative impacts of numerous vulnerabilities may be of greater concern. For example, urban areas might be more impacted when vulnerable to multiple metrics, whereas PET vulnerability could be detrimental to agricultural or forested areas. Similarly, changes in seasonality from a snow dominated system to rain could have profound implications across many sectors.

For this analysis, the 30-year normal climate conditions ~~are~~were compared to decadal ~~(10-year)~~ climate conditions since 1901. In addition, the 30-year ~~normal~~normals for future projections (2041-2070) ~~is~~were compared to the historic range of decadal climate data. ~~While this may~~ While comparing 30-year normals in a decadal analysis might appear to be a discrepancy in the analysis, ~~it~~the intention was ~~included intentionally to represent a conservative approach to quantifying~~to conservatively quantify vulnerability indices. ~~Normal conditions are averaged over a 30~~Thirty-year ~~period and therefore~~ normals exhibit less variability than decadal averages or annual averages. ~~By examining the past variability of the~~By comparing decadal averages ~~since 1901, we use a period that exhibits variability without being an entirely smooth dataset. We then compare that~~ to the 30-year future climate ~~normal, which inherently has much less variability. By using this approach, we recognize that~~normals, we are not treating past data ~~in~~ the same ~~manner~~ as ~~we treat~~ future climate projections. ~~We suggest that~~However, the resulting vulnerability conclusions are conservative, because if we had used decadal projections for future climate data, variability in the range of output would have ~~been more variable. Decadal data would potentially have~~ increased and our vulnerability indices could have increased for all parameters ~~except those that are already at the maximum but should not have decreased the index in any case~~.

~~In Fig. 8, examples are provided (Napa-Sonoma Valley, Willamette Valley, and Mt. Hood) to illustrate how analyses, like the HLVA approach, can assist natural resource managers, business owners, or other stakeholders to understand the potential impacts that changes in climate may have on their environment and the local bottom line. It is necessary for a stakeholder to have an idea of the parameters most important to their ecosystem, industry, or resource of interest, and it should prove useful for land and resource managers that are seeking location specific information about potential climatic impacts (Glick et al., 2011; Lawler et al., 2010).~~

~~Important stakeholders in the western U.S. that may be expected to experience impacts from hydrological changes associated with climate include the wine and skiing industries. The Napa-Sonoma and Willamette Valleys are economically important for their grape vineyards and associated wineries. The Willamette Valley is recognized for~~

~~the quality of its pinot noir varietals (http://wine.appellationamerica.com/wine-region/Willamette-Valley.html), which require narrower temperature ranges than other grape cultivars (Burakowski and Magnusson, 2012; Jones et al., 2010). Due to the importance of the pinot noir varietal to viticulturists in the Willamette Valley, they are likely more concerned with changes in temperature than FMI. The Napa-Sonoma region is recognized for a wider variety of grape cultivars (http://wine.appellationamerica.com/wine-region/Napa-Valley.html, Elliott-Fisk, 1993) that have higher tolerance for temperature fluctuations than the pinot noir varietals commonly grown in the Willamette Valley (Jones et al., 2010). Figure 8 indicates that both the Willamette Valley and Napa-Sonoma have temperature vulnerability indices of ten out of ten, and both have FMI vulnerability indices of three out of ten. These index values suggest that both locations are projected to have future temperatures that are significantly different than the historic observed temperatures. However, the Willamette Valley pinot noir vineyards may have more cause for concern, since pinot noir grapes are documented to be more sensitive to temperature. In the Napa and Sonoma Valleys, there may be less need for concern with temperature than in the Willamette Valley. In addition, while both locations have the same FMI vulnerability indices, Fig. 8 illustrates that FMI projections for Napa-Sonoma are much more variable than for the Willamette Valley. Thus, there is more uncertainty in the modeled water availability for Napa-Sonoma. Taken at face value, these modeled results suggest that a vintner growing warm temperature grape species in the Willamette Valley may have more confidence in his investments relative to a vintner in Napa-Sonoma, where there is more uncertainty regarding long-term water availability.~~

~~The skiing industry is also an important economic contributor. According to Burakowski and Magnusson (2012), the difference in economic impact between a high and low snowfall year for the State of Oregon is $38.1 million, while California is estimated to lose more than $75 million in low snow years. Mt. Hood is well known for its recreational snow sports and winter tourism in Oregon and would be impacted differently by the seven metrics than the Willamette and Napa-Sonoma examples (Fig. 8). Thus, resource managers and business leaders at Mt. Hood are likely more concerned about snow accumulation in their watershed than those in the wine and grape industries (although grape grower's ability to irrigate may be impacted by snow accumulation in the region). According to our analyses, Mt. Hood has a snow vulnerability index of seven out of a maximum of ten. The analysis of seasonality suggests some chance of a shorter ski season due to the spring runoff occurring earlier during the winter season.~~

4.2 Hydrologic Response and Hydrologic Landscape Classification

The HL Class for an AU can provide insight into its hydrological response, given changes in the ~~Even though these conditions have occurred in the past (Fig. 8), this may be much more deleterious to the economics of the modern or future ski industry than it was in the 1900s, because it contributed much less to the historic economy.~~

~~The~~ quantity (~~as indicated by the~~ FMI) ~~and~~or timing ~~(as indicated by the seasonality of the water~~ of surplus~~)~~ ~~of moisture availability~~ water (seasonality) on a landscape. Yet these factors only account for a portion of the water balance ~~for an area. The FMI and seasonality are assumed to be proxies for the quantity and timing of moisture availability, but~~. However, when moisture is available as surface runoff, it may ~~then~~ infiltrate into the ground or act as surface runoff~~.~~ ~~Water may infiltrate the surface layer of soil (~~, depending on the ~~soil~~HL surface permeability~~) and~~ class. Water may enter ~~into the subsurface layers (depending on the vertical conductivity of the subsurface layers). The velocity of water~~and flow through the subsurface layers ~~that flows~~(depending on the HL subsurface permeability) towards a stream channel~~ depend upon the horizontal conductivity of the subsurface layers. Thus, if~~. If the water was ~~retained~~directed as surface or subsurface runoff, it may be transported more quickly in the downhill direction and into a stream channel depending upon the HL terrain class, which governs steepness~~ of the terrain (included in the HL classification).~~. As it relates to streamflow, the unique combination of the five HL characteristics (climate, seasonality, surface permeability, subsurface permeability, and terrain) allows for the ~~estimation of catchment ~~hydrologic ~~responses~~response to be assessed relative to changes in temperature and climate (Leibowitz et al., 2014; Patil et al., 2014). ~~The HL approach has proved useful for streamflow prediction in gaged basins for some HL classes and should be useful in many ungaged basins as well. However, this paper illustrates how the HL approach can help to assess climatic and hydrologic vulnerability across large spatial scales. The three examples we provided, show how the HLVA method could be useful to resource managers for considering how future climate conditions may impact important economic and conservation resources (for additional examples refer to the appendix (2).~~At its most coarse application as it relates to this study, the transition from spring to winter seasonality for the Mt. Hood case study would result in a shorter ski season with snow conditions that could be less ideal for winter sports. However, this transition would also have many downstream impacts that could include flooding or habitat impacts. The HL approach could also be used to determine any relationships between HL characteristics and hydrologic vulnerability, while case studies can show how the HLVA could be useful.

4.3 Case studies

Case studies are useful for illustrating how future climate conditions may impact important economic and conservation resources. It is necessary for a stakeholder to understand the parameters most important to their ecosystem, industry, or resource of interest, so that they can utilize location specific information about their potential climatic impacts (Glick et al., 2011; Lawler et al., 2010). In Fig. 5, case study examples (Mt. Hood (Site #7), Willamette Valley (Site #9), Napa-Sonoma Valley (Site #28)) demonstrate how the HLVA can assist in understanding how climate can impact important local water resources.

The wine and ski industries are important stakeholders in the western U.S. that may experience impacts from hydrological changes. The Napa-Sonoma and Willamette Valleys are known for their vineyards and associated wineries. Regarding their HL characteristics, they differ in their FMI class (Willamette is wet, whereas, Napa-Sonoma is moist) and their seasonality (Willamette has a fall seasonality, while Napa-Sonoma has a winter seasonality). Due to the importance of the pinot noir varietals in the Willamette Valley (Olen and Skinkis, 2018) and its temperature sensitivity (Burakowski and Magnusson, 2012; Jones et al., 2010), local viticulturalists are likely more concerned with changes in temperature than FMI. The Napa-Sonoma region is recognized for a variety of grape cultivars (Elliott-Fisk, 1993) that are less sensitive to temperature fluctuations (Jones et al., 2010). Both the Willamette Valley and Napa-Sonoma have temperature vulnerability indices of ten out of ten, and both have FMI vulnerability indices of three out of ten (Fig. 5). These indices suggest that both locations are projected to have future temperatures that are different than historic temperatures. However, the Willamette Valley pinot noir grapes are more sensitive to temperature than in the Napa and Sonoma Valleys. In addition, while both locations have the same FMI vulnerability indices, Fig. 5 illustrates that FMI projections for Napa-Sonoma are much more variable than for the Willamette Valley. Thus, there is more uncertainty in the modeled water availability for Napa-Sonoma. These results suggest that a vintner growing warm temperature grapes in the Willamette Valley may have more confidence in their investments relative to a vintner in Napa-Sonoma, where there is more uncertainty regarding long-term water availability.

The skiing industry is economically important, and the impact between a high and low snowfall year for the State of Oregon is $38.1 million, while California is estimated to lose more than $75 million in low snow years (Burakowski and Magnusson, 2012). Mt. Hood is known for its winter snow sports and tourism and would be impacted differently by the seven metrics than the Willamette and Napa-Sonoma case studies (Fig. 5). Thus, resource managers and business leaders at Mt. Hood are likely more concerned about snow accumulation in their watershed than those in the wine and grape industries (although grape grower's ability to irrigate may be impacted by snow accumulation in the region). According to our analyses, Mt. Hood is generally characterized by having a spring seasonality and has a snow vulnerability index of seven out of a maximum of ten. Also, the analysis of HL seasonality suggests some chance of a shorter ski season due to the risk of spring runoff occurring earlier and imposing on the winter season. Even though these conditions have occurred in the past (Fig. 5), this may be much more deleterious to the economics of the future ski industry than it was in the 1900s, because it contributed much less to the historic economy (for additional examples refer to Appendix A2).

5 Summary and conclusions

The hydrologic landscapes (HL) concept ~~has proved~~is useful for gaining a better understanding of hydrologic ~~behaviour~~behavior at the assessment unit and watershed scales across large geographic regions. By applying the HL concept to climatic and vulnerability analyses, we provide a planning approach that allows resource managers to ~~consider historic and projected~~determine how vulnerable they are to changes associated with climate ~~behavior in their long-term planning efforts so they can better assess~~that are important for a particular industry or application. Assessment of expected hydrologic response based upon physical and climatic characteristics has the potential to offer further insight into the idiosyncrasies of the nature of the threats faced by a stakeholder or industry across large geographic areas. This will allow them to make informed decisions about the risk imposed by potential changes~~.~~ that could affect their long-term planning efforts. The methodology also allows stakeholders to focus on ~~particular~~specific areas of interest, which provides the flexibility necessary for the information to be relevant across applications and sectors. By applying the modified Wigington et al. (2013) ~~HL~~ approach across the western ~~US,~~U.S., resource managers will ~~gain a better understanding~~be able to base management decisions on assessments of ~~the projected vulnerability~~climatic impacts of water resource ~~availability in a large portion of the United States~~vulnerability.

~~5~~6 Data availability

The geospatial data files (Jones et al., 2020) will be uploaded to the GeoPlatform ~~(https://www.geoplatform.gov/)~~(https://www.geoplatform.gov) and EPA Environmental Dataset Gateway ~~(https://edg.epa.gov/).~~(https://edg.epa.gov). Data cannot be made publicly available and the DOI link cannot go activated until the paper is published per internal U.S. EPA policy.

~~6~~7 Code availability

Authors may deposit code in a FAIR-aligned repository/archive upon final acceptance of the manuscript for publication.

~~7~~8 Video abstract

No ~~Video~~video abstract is available at this time.

~~8~~9 Author contribution

CJ and SL conceptualized the study with significant input from KS. CJ performed the formal analyses, investigation, developed the methodologies (with input from SL, KS, and RC), managed the project, developed the model code, performed the analyses, developed the final figures and tables, and wrote draft versions of the manuscript, and incorporated co-author feedback into the final version of the manuscript. SL supervised the project and performed project administration. RC contributed technical expertise regarding spatial data analyses and familiarity with hydrologic landscapes data analyses. RC and LS developed the subsurface permeability datasets. PM and CW provided the data and advice regarding the use of the future climate projections and the processing of those datasets.

~~9 Acknowledgements~~

10 Acknowledgments

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Protection Agency, administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and EPA, and also through Student Services Contract #EP-15-W-000041. The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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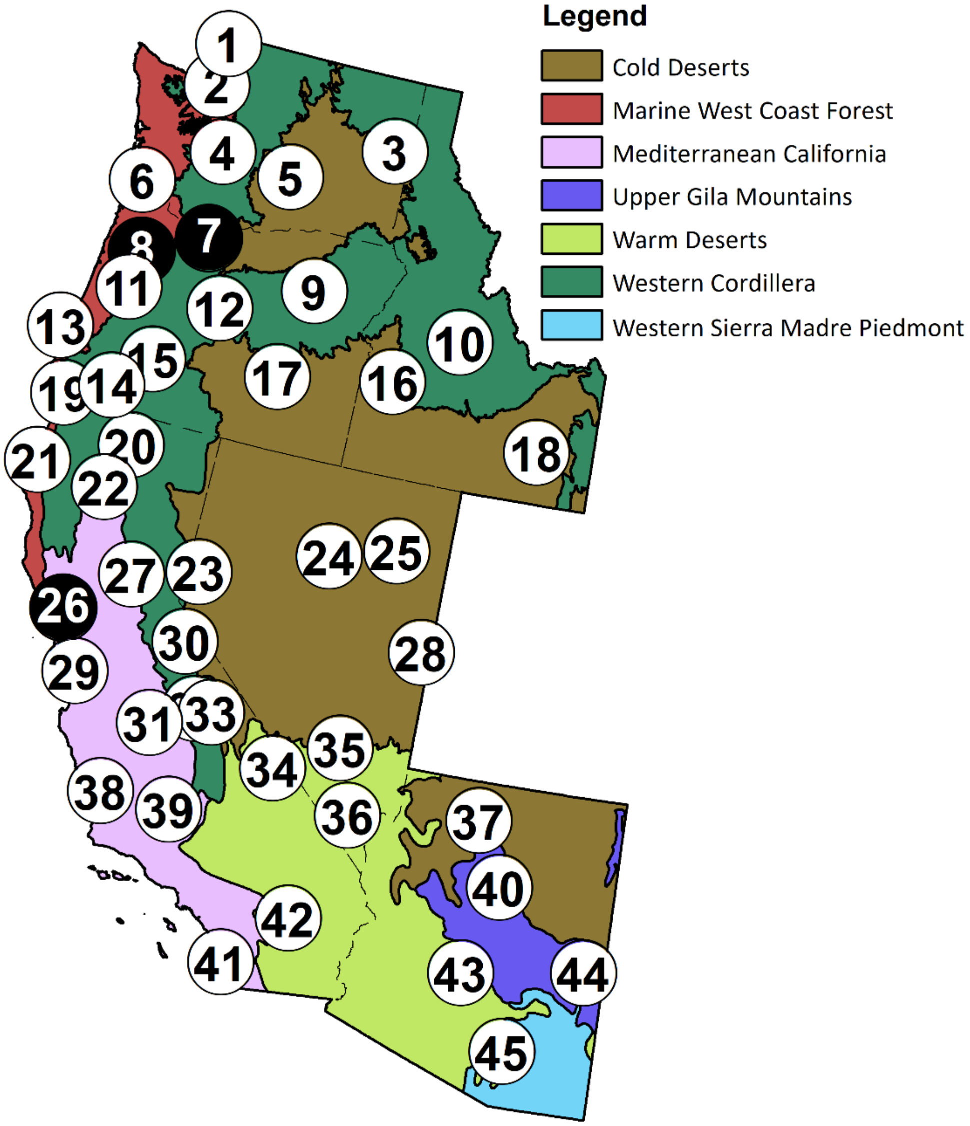
~~11~~12 Figures



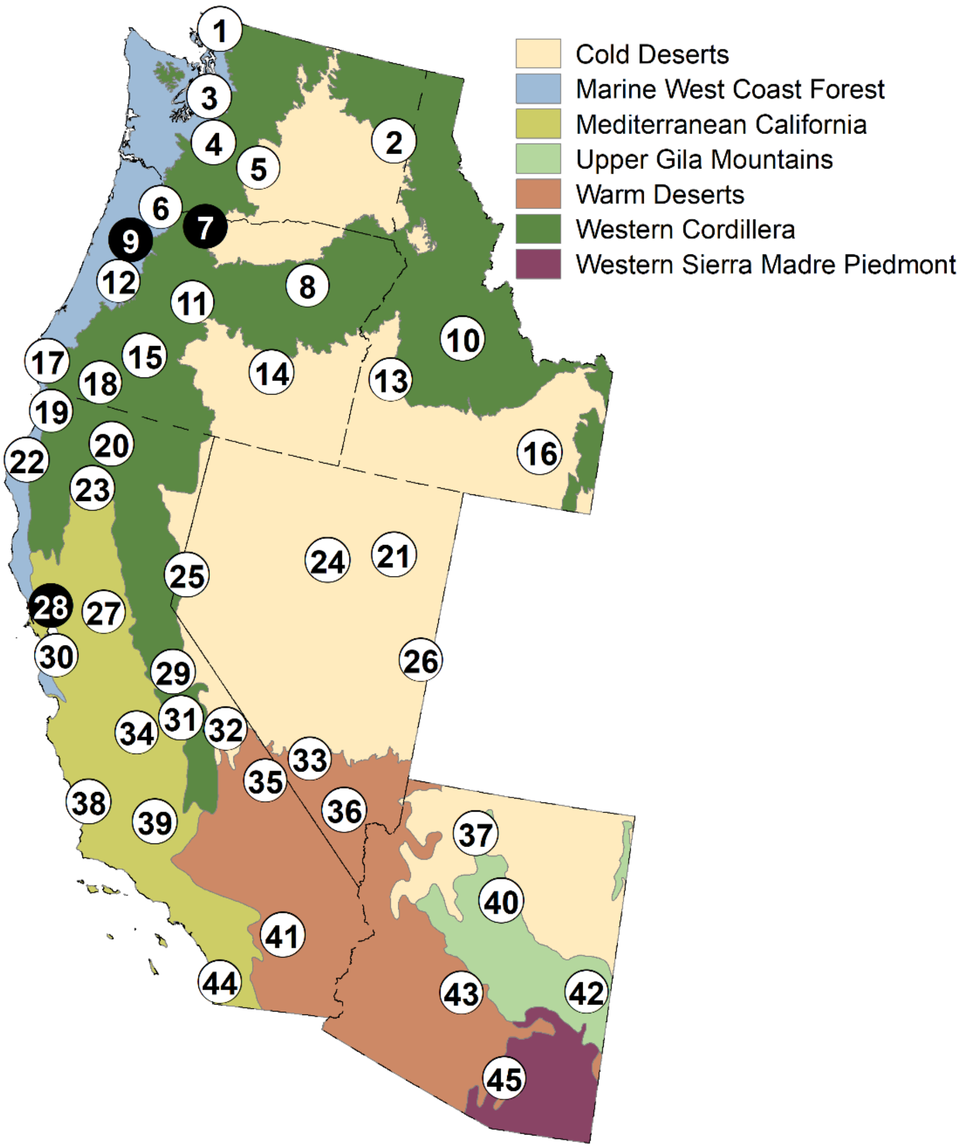


Figure ~~1.~~1. Study area showing map with the six states of WA, OR, ID, CA, NV, and AZ. Also shown are the ~~7~~seven EPA Level II Ecoregions (https://www.epa.gov/eco-research/ecoregions-north-america) and 45 locations identified by numbered circles with three ~~example~~case study locations in black circles (Table 2).

State boundaries are indicated by black dashed lines.

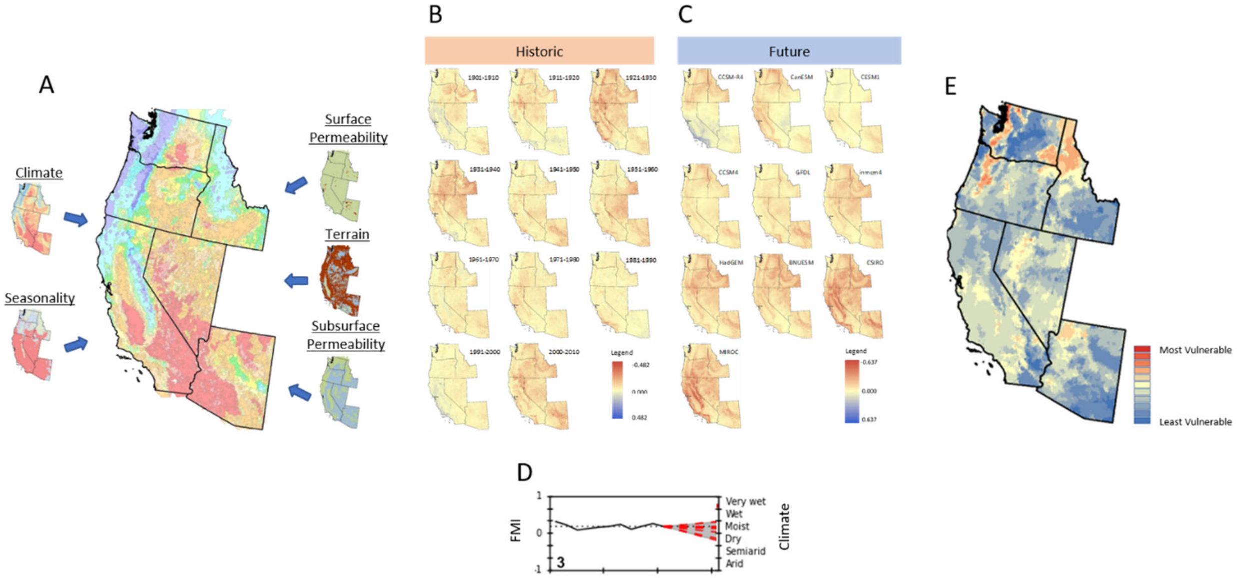


Figure 2. Mapping of hydrologic vulnerability. A) Hydrologic landscape map is developed for six western states using 1971-2000 normals for climate (Feddema Moisture Index; FMI) and seasonality, along with surface permeability, terrain, and subsurface permeability geophysical data. B) Historical decadal analysis is run from 1901 through 2010 for each of seven metrics: monthly temperature, precipitation, potential evapotranspiration, surplus water, snow water equivalent, FMI (shown), and seasonality. C) Future predicted behavior is estimated for each of the seven metrics, based on ten climate model projections (FMI shown). D) Vulnerability is then defined as the number of climate projections that lie outside of the historical two standard deviation threshold (example for FMI from Napa-Sonoma shown). E) Vulnerability values are then mapped for each metric across the six-state study area (FMI shown).

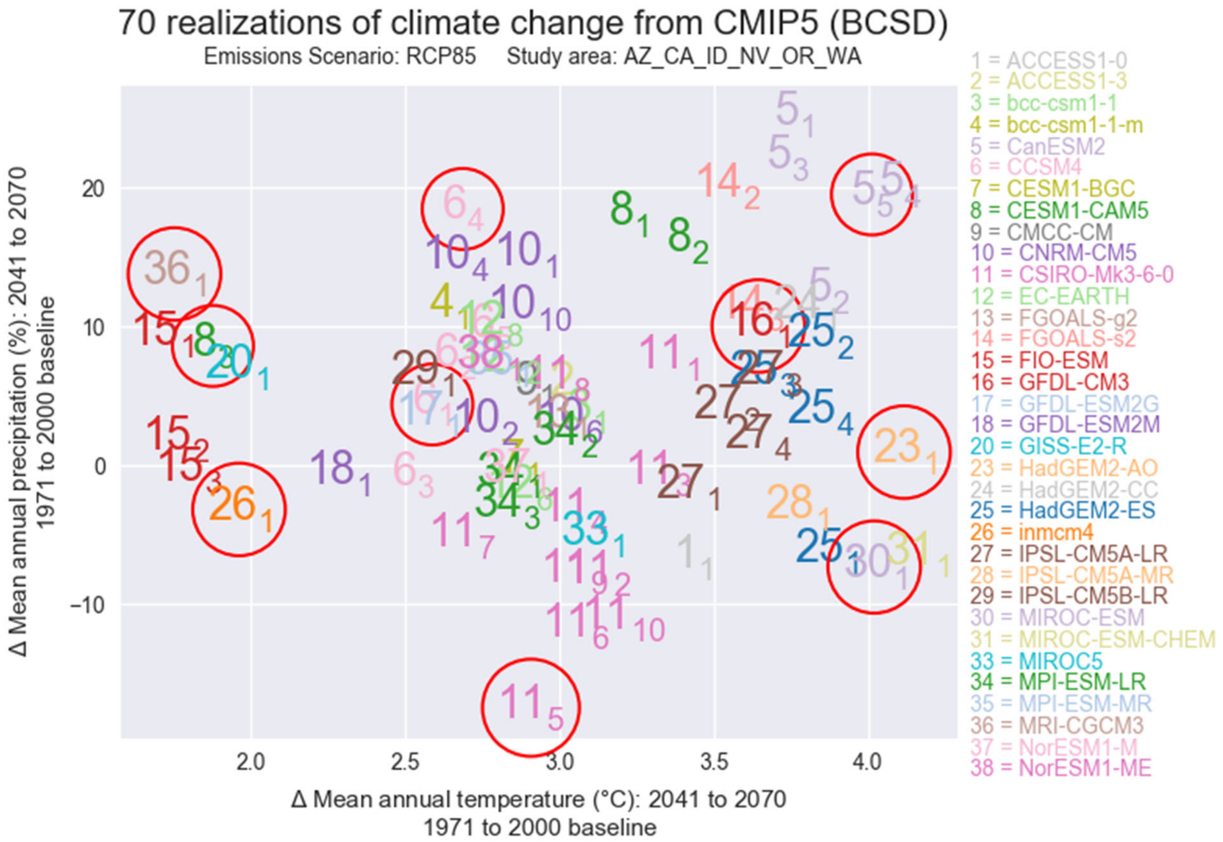
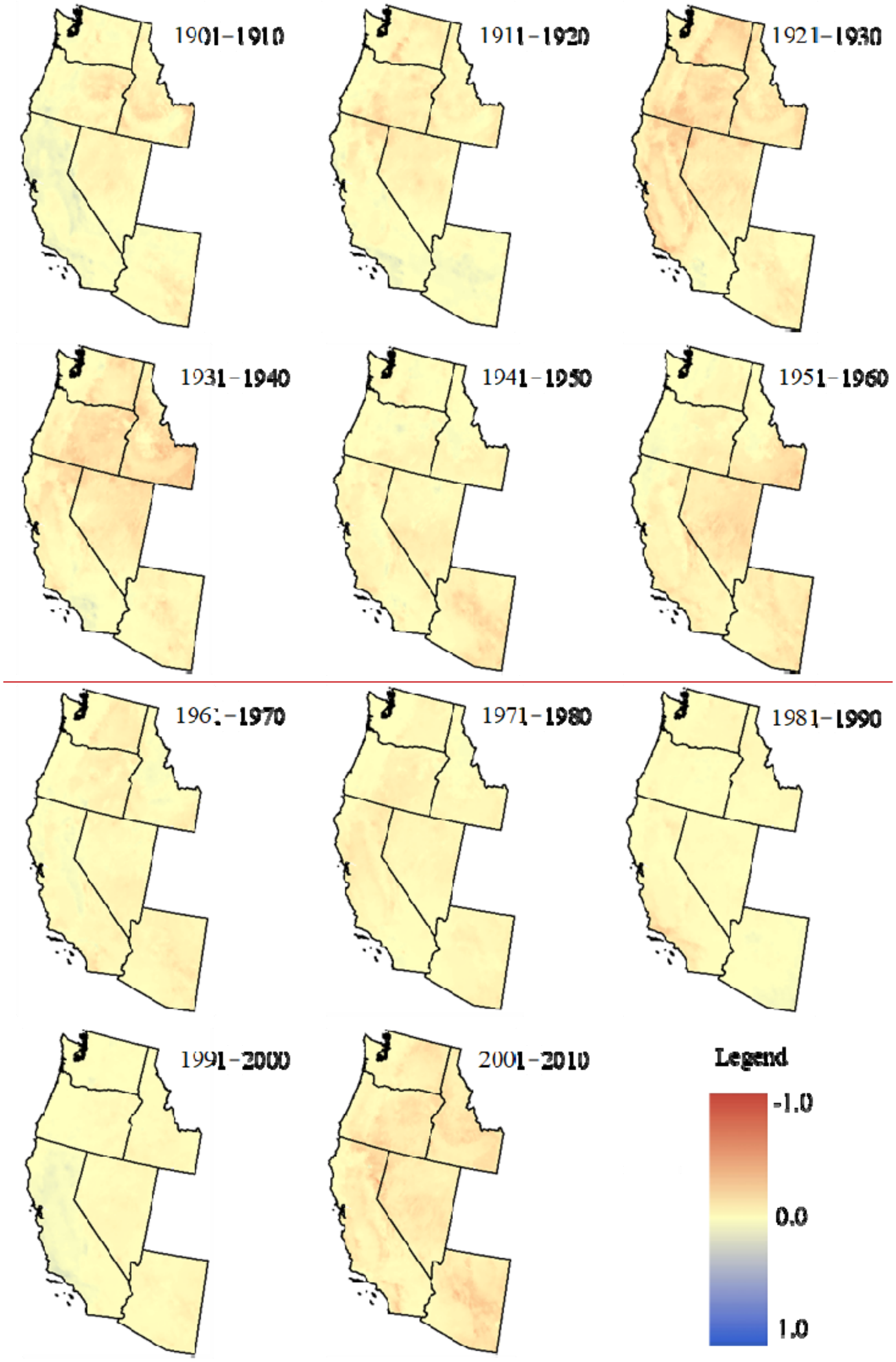
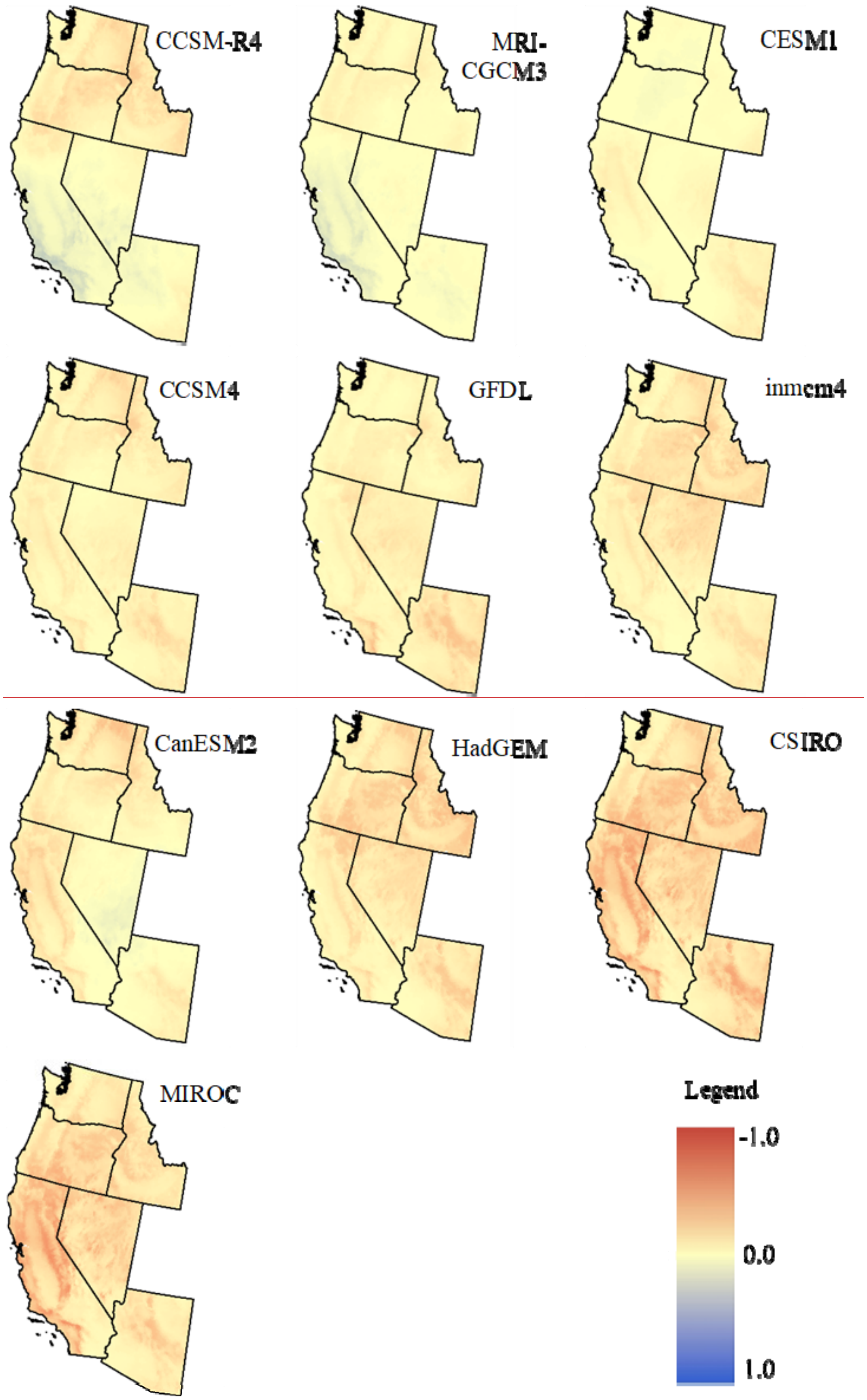


Figure ~~2.~~3. Scatterplot showing the range of mean temperature and precipitation projections for the 2041−2070 climate models across the study area. The circled data points identify the climate projections used in our analyses.

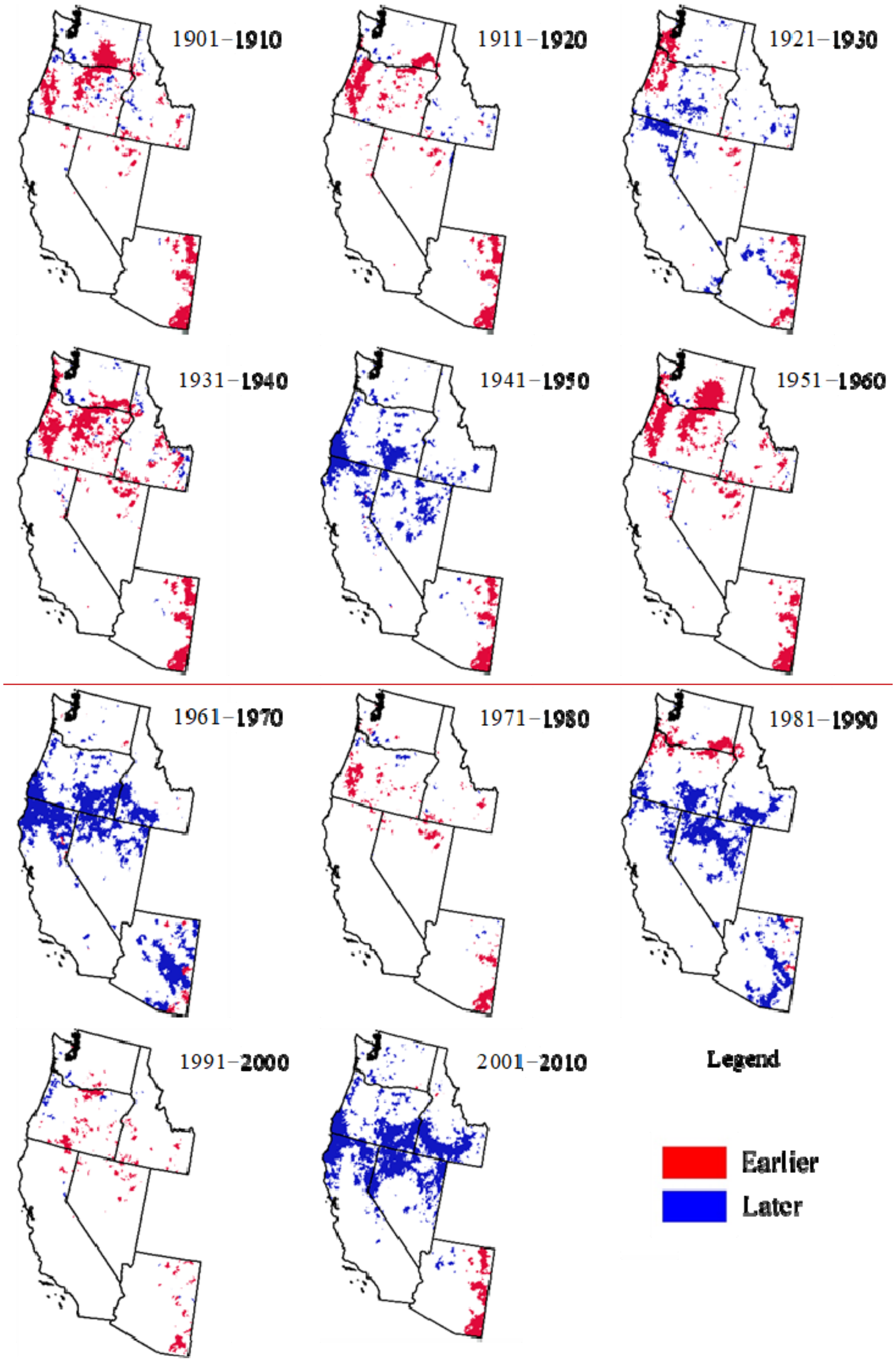
Climate models are enumerated using the key to the right of the scatterplot. Subscripts denote the realization number of each unique projection. Legend colors are used to improve legibility where scatterplot symbols overlap.



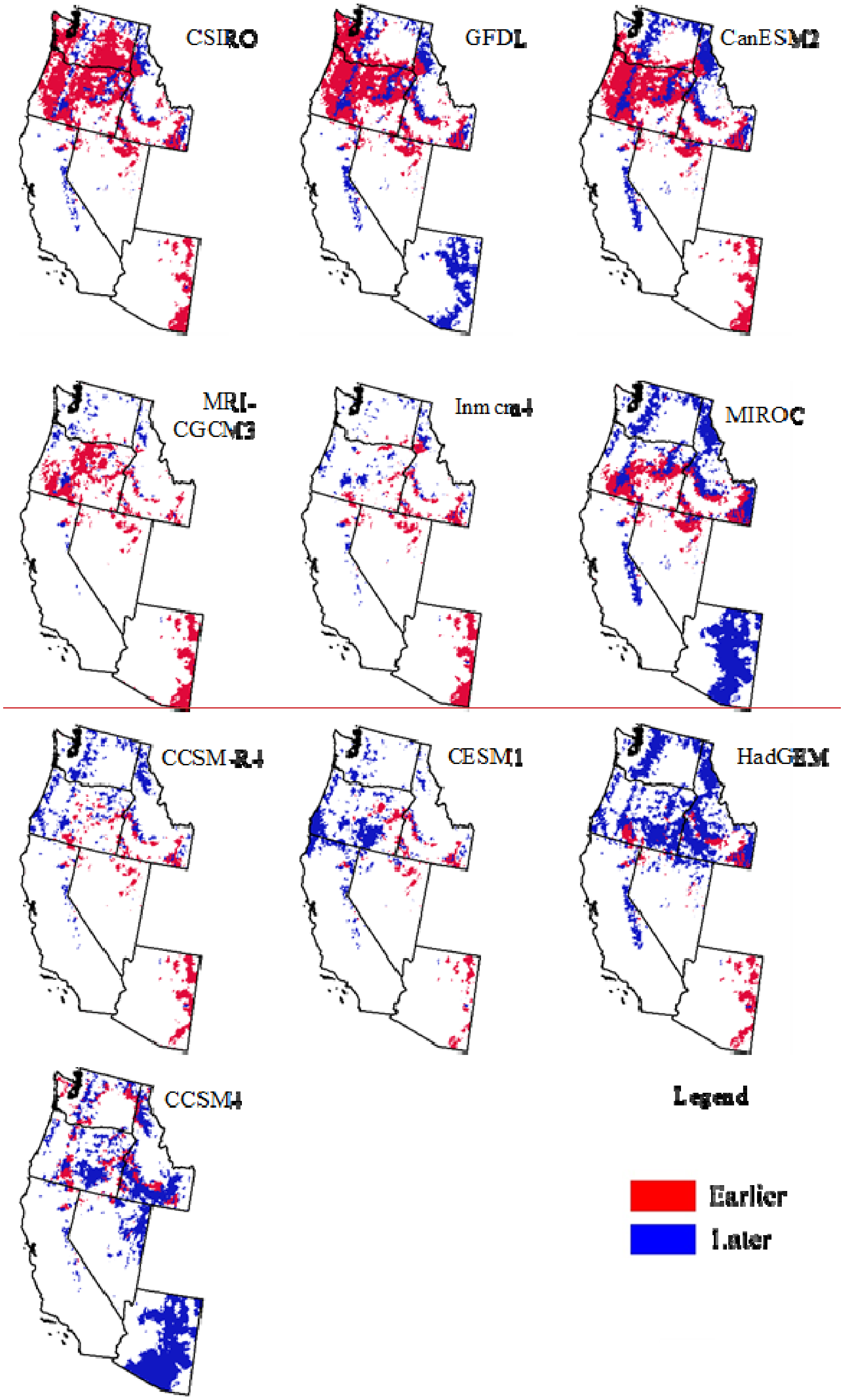
~~**Figure 3. Decadal change in Feddema Moisture Index relative to 1971–2000 normal period. Red and blue colors indicate drier and wetter average conditions than 1971–2000, respectively.**~~



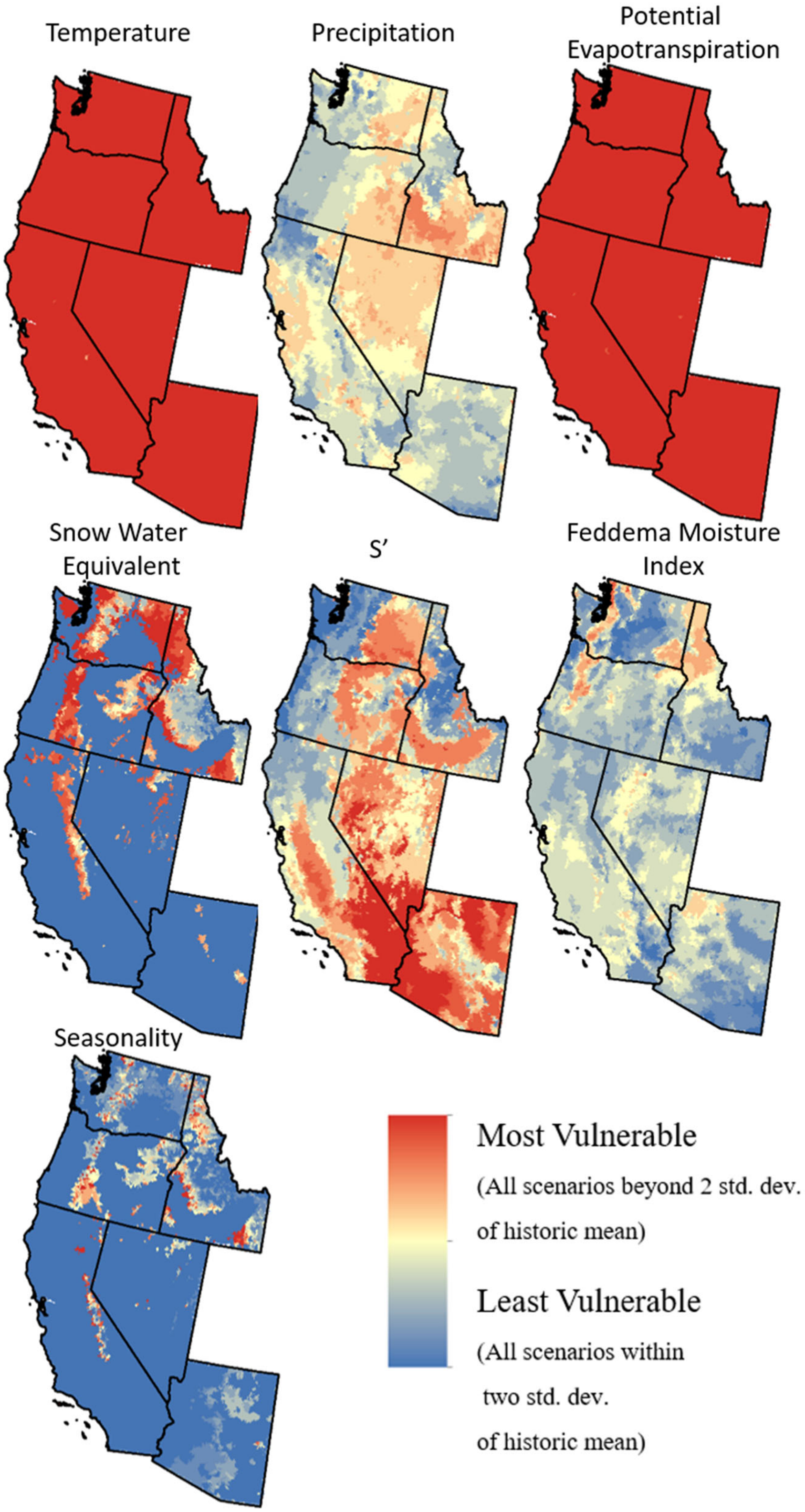
~~**Figure 4. Projected change in Feddema Moisture Index for 2041–2070 relative to 1971–2000 for ten climate models (Table 1). Red and blue colors indicate drier and wetter conditions than the 1971–2000 base period, respectively. Abbreviated model names correlate to those in Table 1.**~~



~~**Figure 5. Decadal change in seasonality of water surplus since 1901 relative to 1971–2000. Red and blue colors indicate earlier and later seasonality than the 1971–2000 base period, respectively.**~~



~~Figure 6. Projected change in seasonality of water surplus for 2041─2070 relative to 1971─2000 for ten climate models. Red and blue colors indicate earlier and later seasonality than the 1971─2000 base period, respectively. Abbreviated model names correlate to those in Table 1.~~


Temperature
Precipitation
Potential Evapotranspiration
Snow Water Equivalent
S′
Feddema Moisture Index
Seasonality
Most Vulnerable
(All scenarios beyond 2 std. dev. of historic mean)
Least Vulnerable
(All scenarios within two std. dev. of historic mean)

~~Figure 7.~~

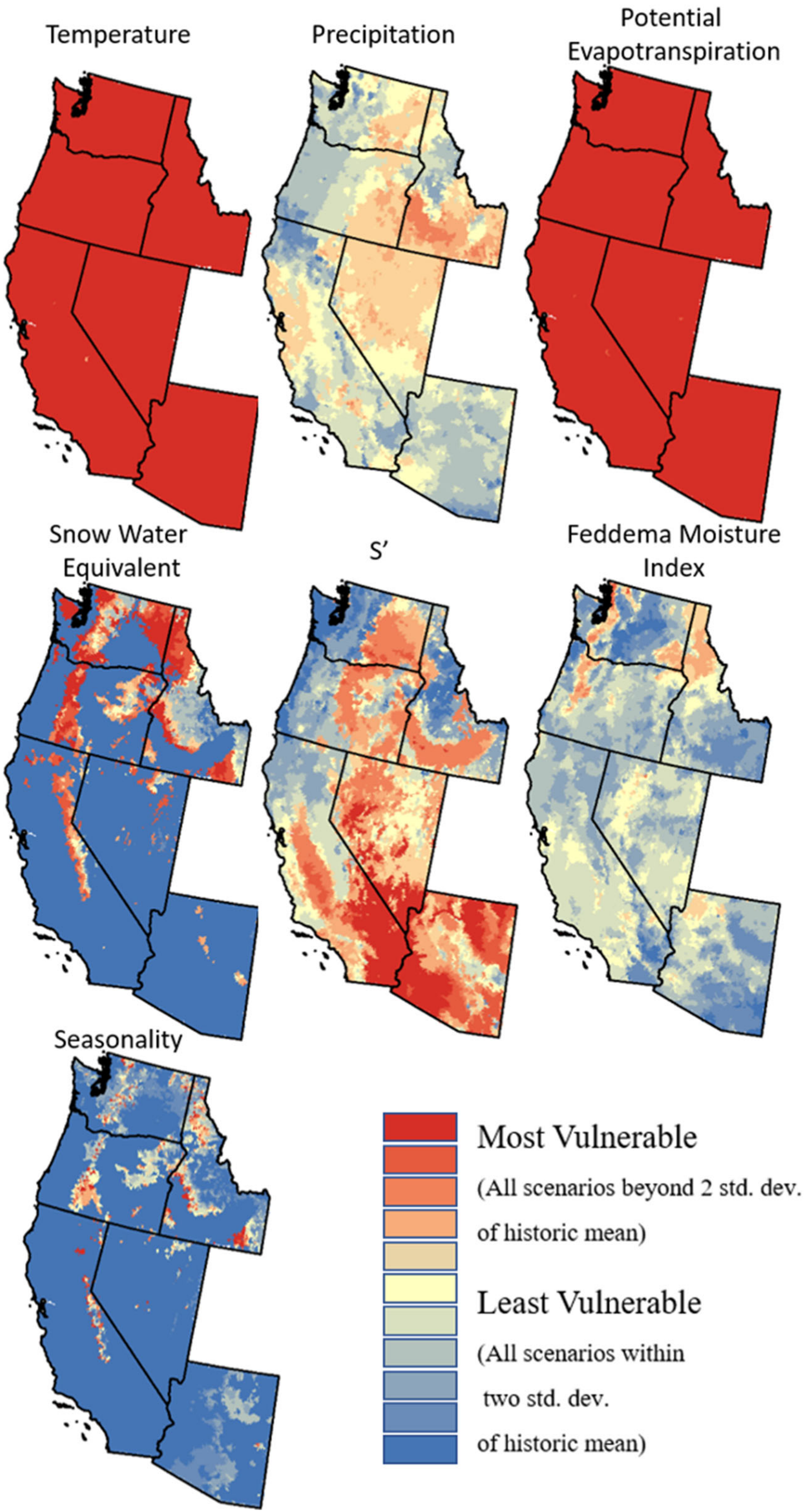
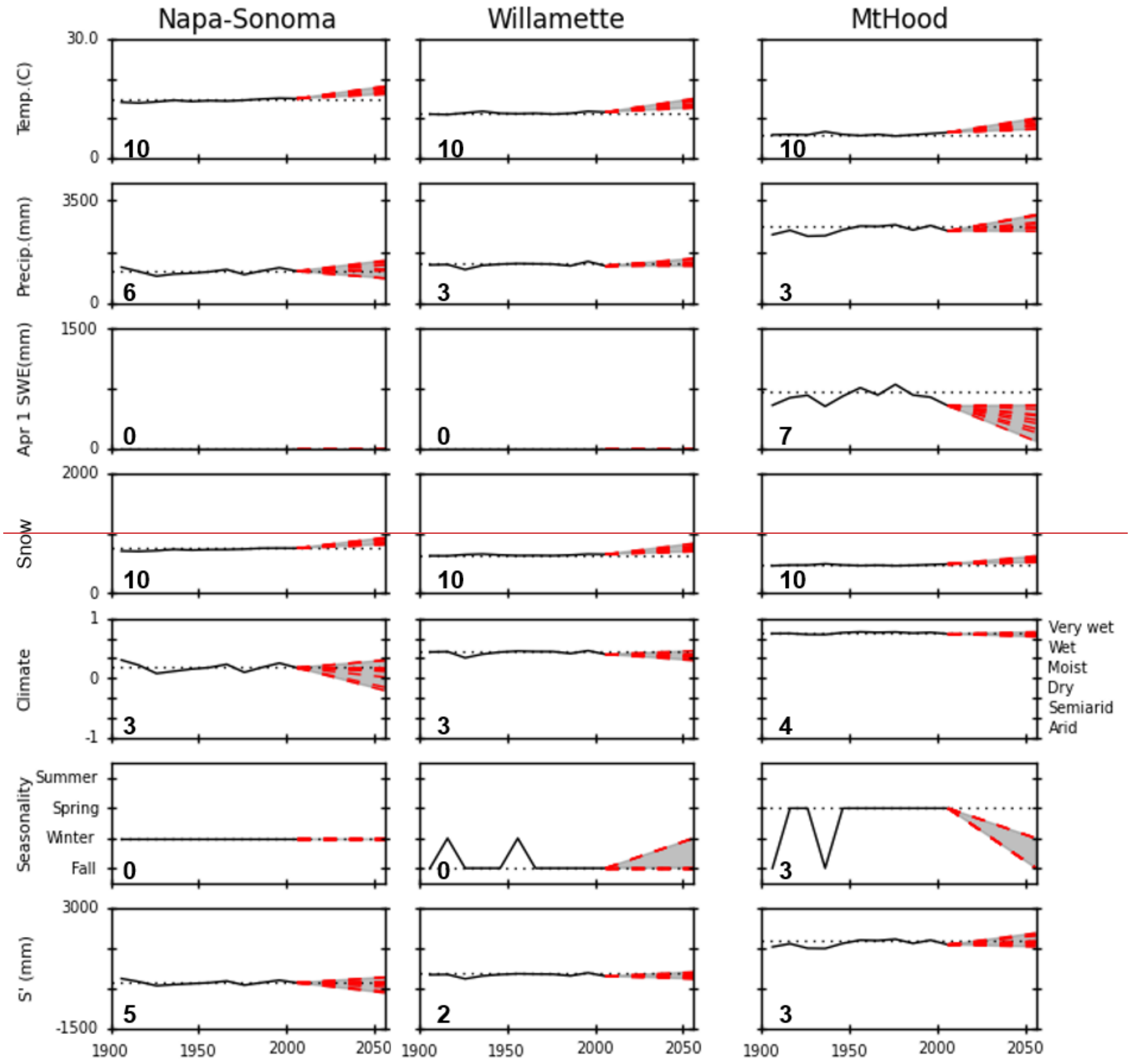


Figure 4. Vulnerability indices for temperature, precipitation, potential evapotranspiration, snow water equivalent (April 1), S' (available water), Feddema Moisture Index, and seasonality. The least vulnerable locations are those projected to be within two-standard deviations of the historic (1901−2010) mean in all ~~nine~~ten climate models.


Napa-Sonoma
Willamette
MtHood
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
6
3
3
Apr 1 SWE(mm)
1500
0
0
0
7
Snow
2000
0
10
10
10
Climate
1
0
-1
3
3
4
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
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3
1900
1950
2000
2050

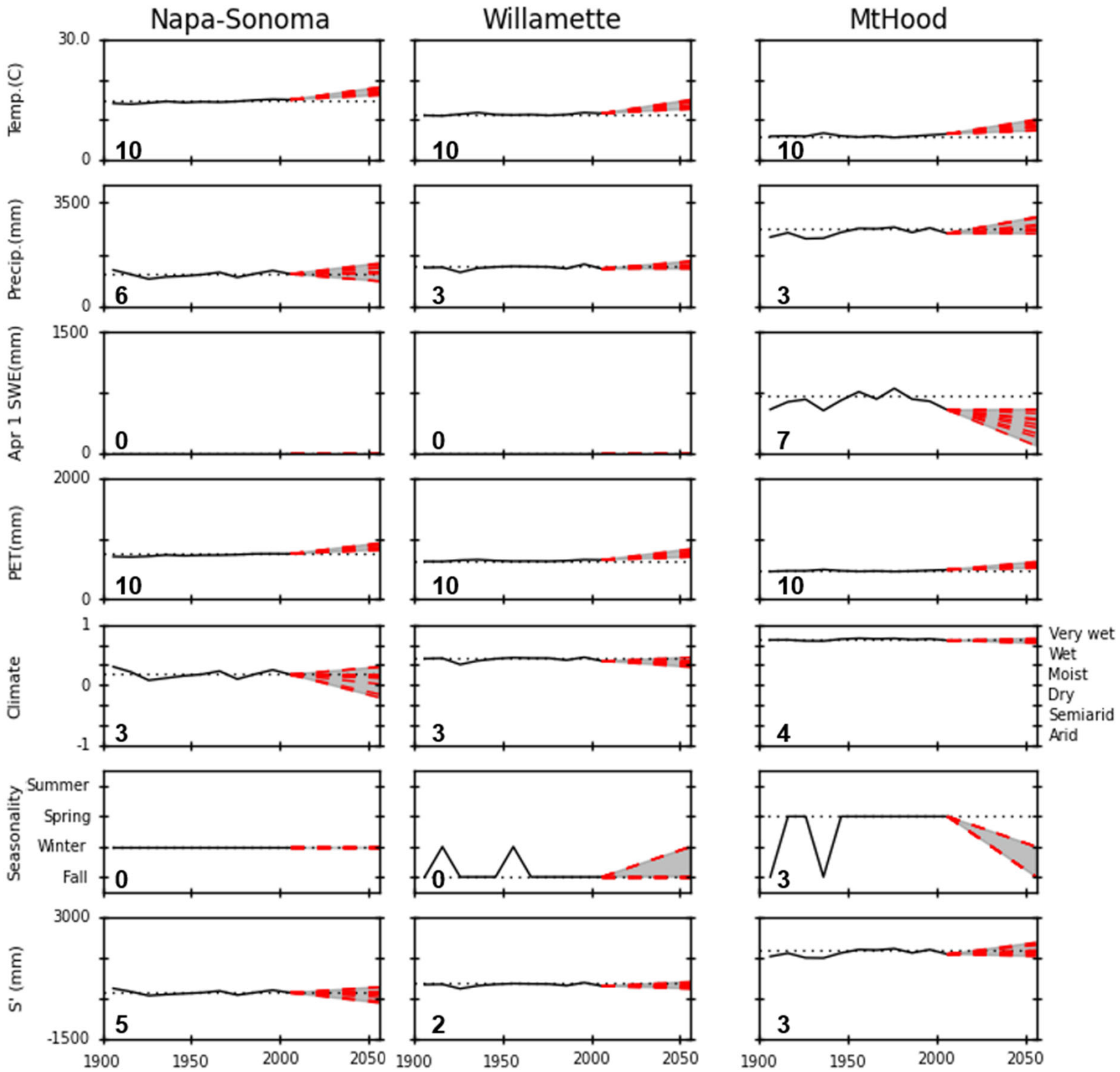


Figure ~~8.~~5. Time series of average decadal temperature, precipitation, snow (April 1 snow water equivalent (mm)), potential evapotranspiration (PET), climate (FMI), seasonality, and available water (S'~~), FMI, and seasonality~~) for three specific locations in the western U.S. For the climate / FMI figures, the FMI values range from 1 to -1 (primary y-axis on the left), whereas the categorical version of the index ranges from arid to very wet (secondary y-axis on the right). Dotted black line represents the 1971−2000 base period; the dashed red line connects the 2001−2010 value to the 2041−2070 climate projections~~.~~ for each of the ten models. The gray shaded area represents the range of model projections. The number in lower left indicates the vulnerability index for the metric and location depicted in the associated graph.

~~12~~13 Tables

Table 1. CMIP5 Climate model summary for 2041−2070 precipitation and temperature data (Bureau of Reclamation, 2014)**.**

WCRP CMIP5 Climate Model	**Model abbreviated name**	**Model realization used herein**	**Abbreviated name used in ~~this paper~~Figure 3 for realization**
Canadian Earth System Model	CanESM2	r5i1p1	CanESM2
Community Climate System Model	CCSM4	r1i1p1	CCSM4
Community Climate System Model	CCSM4	r4i1p1	CCSM4-R4
Community Earth System Model	CESM1	r3i1p1	CESM1
Commonwealth Scientific and Industrial Research Organisation Mark 3.6	CSIRO-Mk3-6-0	r5i1p1	CSIRO
Geophysical Fluid Dynamics Laboratory Coupled Climate Model	GFDL-CM3	r1i1p1	GFDL
Hadley Global Environment Model	HadGEM2-AO	r1i1p1	HadGem
Institute for Numerical Mathematics Climate Model	INM-CM4	r1i1p1	inmcm4
Model for Interdisciplinary Research on Climate	MIROC-ESM	r1i1p1	MIROC
Meteorological Research Institute	MRI-CGCM3	r1i1p1	MRI-CGCM3

Table 2. Summary table for 45 study locations (sorted by decreasing latitude) ~~provides~~providing numeric ID from Fig. 1, total analysis area, dominant HL class (representing climate, seasonality, subsurface permeability, terrain, and surface permeability), percent area represented by dominant HL class, latitude and longitude of the center point of the area, and vulnerability indices for temperature, precipitation, potential evapotranspiration (PET), ~~precipitation,~~ surplus water (S'~~,~~), snow~~,~~ water equivalent (snow), Feddema Moisture Index (FMI), and seasonality.

					Coordinates		**Vulnerability Index**						
Site #	**Name**	**Area (km^2)**	**Dominant HL Class***	**% Dominant Area**	**Lat.**	**Long.**	**Temp.**	**Precip.~~PET~~**	**PET~~Precip.~~**	**S'**	**Snow**	**FMI**	**Seasonality**
1	Bellingham	212	WfLTH	99 %	48.77	-122.45	10	~~10~~5	~~5~~10	1	0	9	0
2	Spokane	592	DfHTH	80 %	47.64	-117.43	10	~~10~~6	~~6~~10	7	10	3	1
3	Seattle	669	WfLTH	78 %	47.60	-122.25	10	~~10~~4	~~4~~10	1	0	5	2
4	~~MtRainier~~Mt Rainier	718	VsLMH	76 %	46.85	-121.79	10	~~10~~4	~~4~~10	2	7	4	2
5	Yakima	438	SfHTH	86 %	46.63	-120.60	10	~~10~~3	~~3~~10	6	0	0	0
6	Portland	932	WfHTH	67 %	45.53	-122.66	10	~~10~~3	~~3~~10	2	0	6	0
7	~~MtHood~~Mt. Hood	834	VsHMH	81 %	45.37	-121.70	10	~~10~~3	~~3~~10	3	7	4	3
8	~~UmatillaNF~~Umatilla NF	2,147	MsLMH	29 %	44.87	-118.70	10	~~10~~6	~~6~~10	3	6	3	4
9	Willamette	1,234	WfHTH	83 %	44.84	-123.14	10	~~10~~3	~~3~~10	2	0	4	0
10	~~ChallisNF~~Challis NF	4,348	WsLMH	74 %	44.55	-114.75	10	~~10~~6	~~6~~10	0	3	2	0
11	Bend	948	SfHTH	68 %	44.21	-121.26	10	~~10~~4	~~4~~10	8	0	3	0
12	Eugene	523	WfHFH	64 %	44.10	-123.15	10	~~10~~3	~~3~~10	1	0	2	0
13	Boise	594	SwHTH	51 %	43.61	-116.24	10	~~10~~8	~~8~~10	8	0	2	0

					Coordinates		Vulnerability Index						
Site #	Name	Area (km^2)	Dominant HL Class*	% Dominant Area	Lat.	Long.	Temp.	Precip.~~PET~~	PET~~Precip.~~	S'	Snow	FMI	Seasonality
14	~~MalheurNWR~~Malheur NWR	1,355	SwHFH	69 %	43.27	-119.04	10	~~10~~6	~~6~~10	7	0	2	0
15	~~CraterLake~~Crater Lake	1,721	WsHTH	45 %	42.98	-122.08	10	~~10~~3	~~3~~10	2	9	3	10
16	Pocatello	349	DwHTH	45 %	42.88	-112.43	10	~~10~~7	~~7~~10	7	0	1	0
17	~~SiskiyouNF~~Siskiyou NF	926	VwLMH	100 %	42.36	-124.29	10	~~10~~2	~~2~~10	0	0	2	0
18	Medford	375	DfLTH	60 %	42.34	-122.89	10	~~10~~1	~~1~~10	5	0	2	0
19	~~SixRivers~~Six Rivers	1,527	VwLMH	100 %	41.63	-123.79	10	~~10~~2	~~2~~10	2	0	4	0
20	~~MtShasta~~Mt Shasta	956	WwHMH	49 %	41.36	-122.23	10	~~10~~1	~~1~~10	2	0	3	0
21	~~RubyMtn~~Ruby Mtn	1,132	DfLTH	44 %	40.68	-115.31	10	~~10~~6	~~6~~10	5	9	4	0
22	Arcata-~~HumboldtCo~~Humboldt Co	2,511	WwLMH	63 %	40.62	-124.01	10	~~10~~3	~~3~~10	2	0	3	0
23	Redding	478	MwHTH	59 %	40.56	-122.38	10	~~10~~2	~~2~~10	2	0	2	0
24	~~BattleMtn~~Battle Mtn	902	SwLMH	75 %	40.09	-116.71	10	~~10~~6	~~6~~10	7	0	4	0
25	Reno	382	SwHTH	40 %	39.54	-119.80	10	~~10~~4	~~4~~10	7	0	3	0

					Coordinates		Vulnerability Index						
Site #	Name	Area (km^2)	Dominant HL Class*	% Dominant Area	Lat.	Long.	Temp.	Precip.~~PET~~	PET~~Precip.~~	S'	Snow	FMI	Seasonality
26	~~GreatBasinNP~~Great Basin NP	38	MsLMH	100 %	39.01	-114.26	10	~~10~~4	~~4~~10	5	0	4	1
27	Sacramento	855	SwHFH	88 %	38.57	-121.39	10	~~10~~6	~~6~~10	7	0	3	0
28	Napa-Sonoma	1,867	MwHTH	61 %	38.37	-122.53	10	~~10~~6	~~6~~10	5	0	3	0
29	~~YosemiteNP~~Yosemite NP	2,455	VsLMH	44 %	37.93	-119.55	10	~~10~~4	~~4~~10	4	9	3	0
30	~~SanFranciscoBay~~San Francisco Bay	3,356	DwHMH	19 %	37.44	-122.29	10	~~10~~6	~~6~~10	5	0	5	0
31	~~SierraNF~~Sierra NF	5,349	WwLMH	31 %	37.17	-119.05	10	~~10~~4	~~4~~10	4	0	2	0
32	~~HighSierras~~High Sierras	2,239	WsLMH	32 %	37.15	-118.81	10	~~10~~2	~~2~~10	4	1	2	0
33	~~NevadaTestSite~~Nevada Test Site	3,121	AwHMH	67 %	36.96	-116.22	10	~~10~~5	~~5~~10	10	0	4	0
34	Fresno	1,393	AwHFH	100 %	36.74	-119.91	10	~~10~~5	~~5~~10	8	0	4	0
35	~~DeathValleyNP~~Death Valley NP	7,862	AwHMH	50 %	36.45	-117.03	10	~~10~~5	~~5~~10	10	0	5	0
36	~~LasVegas~~Las Vegas	977	AwHTH	65 %	36.23	-115.26	10	~~10~~4	~~4~~10	10	0	4	0
37	~~GrandCanyonNP~~Grand Canyon NP	3,475	SwHMH	28 %	36.22	-112.11	10	~~10~~4	~~4~~10	10	0	6	0

					Coordinates		Vulnerability Index						
Site #	**Name**	**Area (km²)**	**Dominant HL Class***	**% Dominant Area**	**Lat.**	**Long.**	**Temp.**	**Precip. ~~PET~~**	**PET~~Precip.~~**	**S'**	**Snow**	**FMI**	**Seasonality**
38	~~SanLuisObispo~~San Luis Obispo	2,653	DwLMH	98 %	35.36	-120.63	10	~~10~~4	~~4~~10	4	0	4	0
39	Bakersfield	3,399	AwHFH	96 %	35.33	-119.14	10	~~10~~4	~~4~~10	9	0	4	0
40	Flagstaff	365	DwHMH	51 %	35.19	-111.60	10	~~10~~3	~~3~~10	4	0	4	0
41	~~JoshuaTreeNP~~Joshua Tree NP	2,599	AwLMH	68 %	33.92	-115.99	10	~~10~~5	~~5~~10	7	0	5	0
42	~~WhiteMtns~~White Mtns	4,855	WfLMH	23 %	33.87	-109.53	10	~~10~~4	~~4~~10	3	0	3	0
43	Phoenix	2,304	AwHFH	63 %	33.52	-112.11	10	~~10~~3	~~3~~10	10	0	2	1
44	~~SanDiego~~San Diego	1,276	SwLMH	37 %	32.90	-117.06	10	~~10~~4	~~4~~10	6	0	4	0
45	Tucson	1,838	AwHTH	62 %	32.19	-110.95	10	~~10~~3	~~3~~10	9	0	1	2

*Climate class (1st letter): V=very wet; W=wet; M=moist; D=dry; S=semiarid; A=arid

Seasonality class (2nd letter): f=fall; w= winter; s=spring; u=summer

Subsurface permeability class (3rd letter): L=low; H=high

Terrain class (4th letter): M=mountain; T=transitional; F=flat

Surface permeability class (5th letter): L=low; H=high

Table 3. Percent of area of each HL category and classification within the six-state region (1971−2000)

Category	Classification	Area (%)
Climate	Arid	21 %
	Semi-arid	34 %
	Dry	15 %
	Moist	9 %
	Wet	14 %
	Very wet	7 %
Season	Spring (AMJ[1])	13 %
	Summer (JAS[2])	1 %
	Fall (OND[3])	24 %
	Winter (JFM[4])	63 %
Subsurface ~~Perm.~~Permeability	Low	40 %
	High	60 %
Terrain	Flat	7 %
	Transitional	63 %
	Mountain	30 %
Surface ~~Perm.~~Permeability	Low	2 %
	High	98 %

[1] AMJ: April, May, and June

[2] JAS: July, August, and September

[3] OND: October, November, and December

[4] JFM: January, February, and March

Table 4. Hydrologic landscape characteristics of assessment units identified as vulnerable (having a vulnerability index greater than 7 on a scale of 10) for each metric.

% Assessment units that share HL classification

Vulnerability Parameter	**Climate**^{1}		**Seasonality**^{2}		**Subsurface ~~Perm.^{3}~~Permeability^3**		**Terrain**^{4}		**Surface ~~perm.^{3}~~permeability^3**	
~~Snow~~Temperature	~~75~~70 %	D, ~~M~~S, or ~~W~~A	87 %	f or ~~s~~w	~~53~~60 %	~~L~~H	~~82~~93 %	M or T	~~100~~98 %	H
~~FMI~~Precipitation	~~71~~72 %	~~V~~D or ~~W~~S	~~65~~79 %	f or w	~~75~~71 %	~~L~~H	~~75~~97 %	M or T	~~100~~98 %	H
~~Seasonality~~PET	~~75~~70 %	~~W~~D, S, or ~~M~~A	~~76~~87 %	~~s~~f or w	~~51~~60 %	H	~~83~~93 %	M or T	~~99~~98 %	H
Surplus water (S')	92 %	A or S	79 %	w	75 %	H	87 %	M or T	99 %	H
~~ppt~~Snow water equivalent (SWE)	~~72~~75 %	D, M, or ~~S~~W	~~79~~87 %	f or ~~w~~s	~~71~~53 %	~~H~~L	~~97~~82 %	M~~ or T~~	~~98~~100 %	H
~~tmean~~FMI	~~70~~71 %	~~D, S,~~V or ~~A~~W	~~87~~65 %	f ~~or w~~	~~60~~75 %	~~H~~L	~~93~~75 %	M~~ or T~~	~~98~~100 %	H
~~PET~~Seasonality	~~70~~75 %	~~D, S,~~W or ~~A~~M	~~87~~76 %	~~f or w~~s	~~60~~51 %	H	~~93~~83 %	M~~ or T~~	~~98~~99 %	H

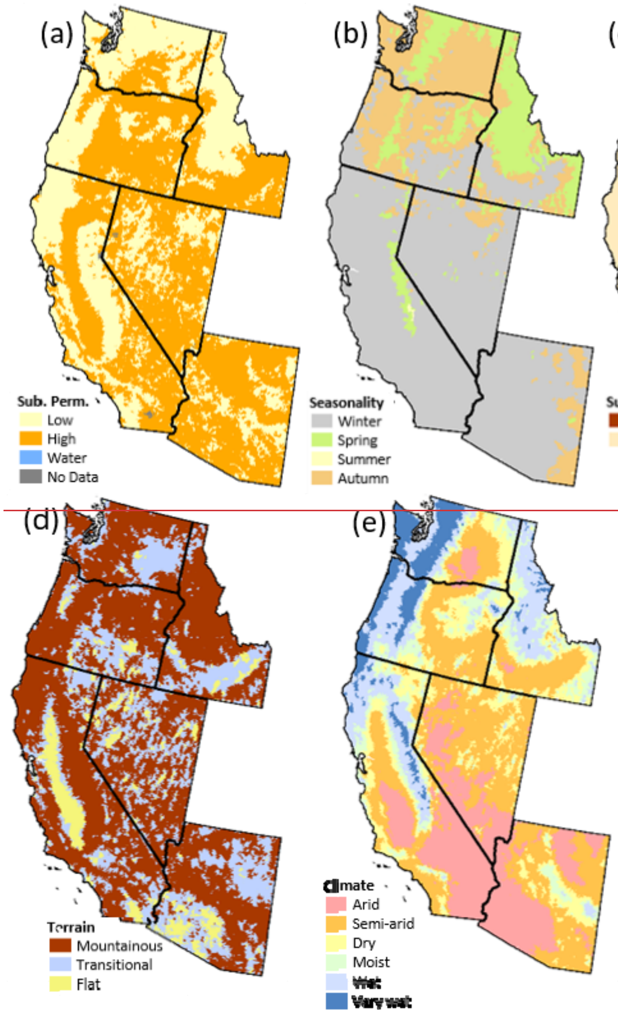
[1] A=arid, S=semiarid, D=dry, M=moist, W=wet

[2] f=fall, w=winter, s=spring

[3] L=low, H=high

[4] T=transitional, M=mountainous

Appendix A


(a)
Sub. Perm.
Low
High
Water
No Data
(b)
Seasonality
Winter
Spring
Summer
Autumn
(c)
Surf. Perm.
Low
High
(d)
Terrain
Mountainous
Transitional
Flat
(e)
Climate
Arid
Semi-arid
Dry
Moist
Wet
Very wet

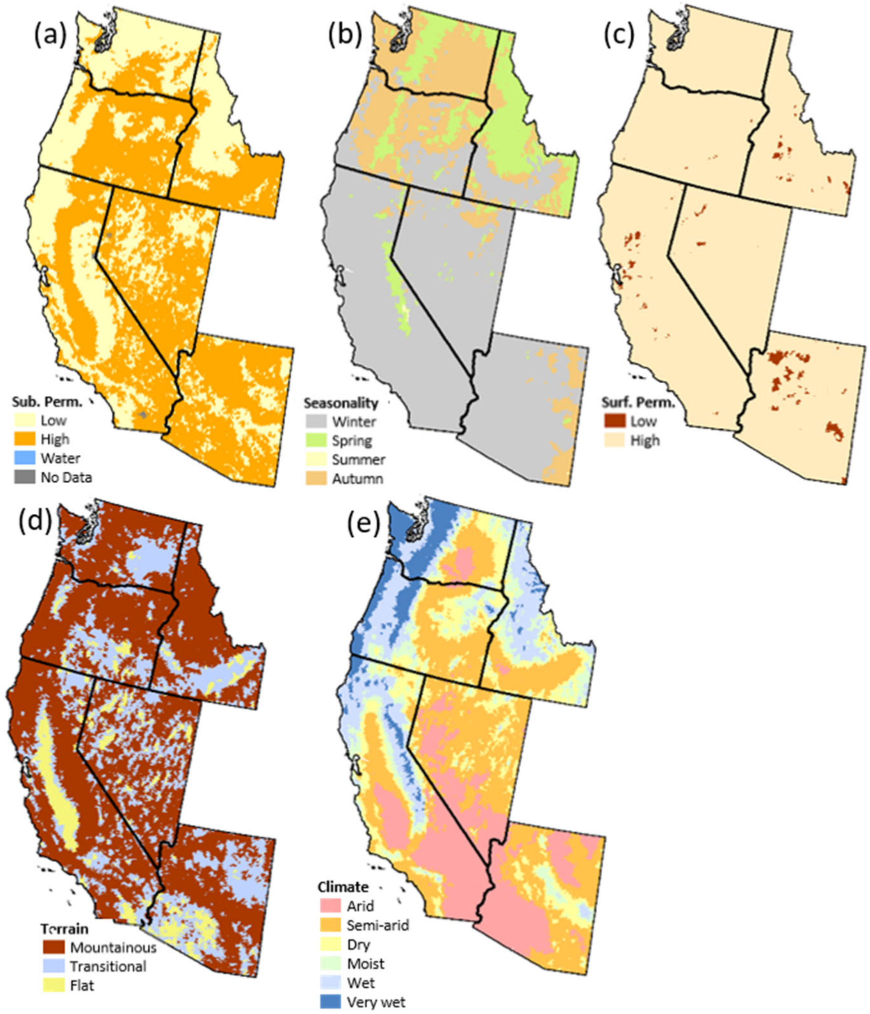
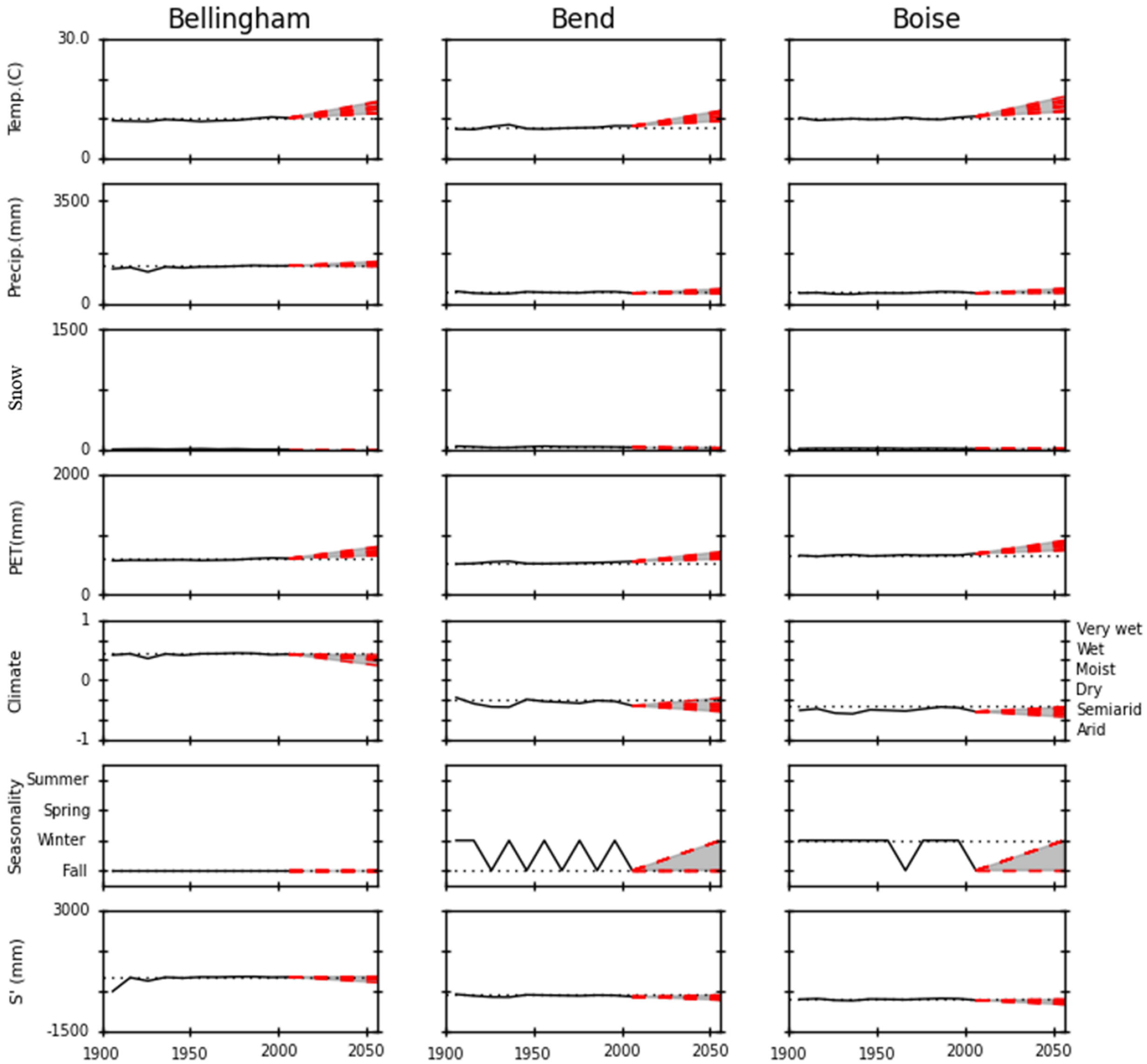
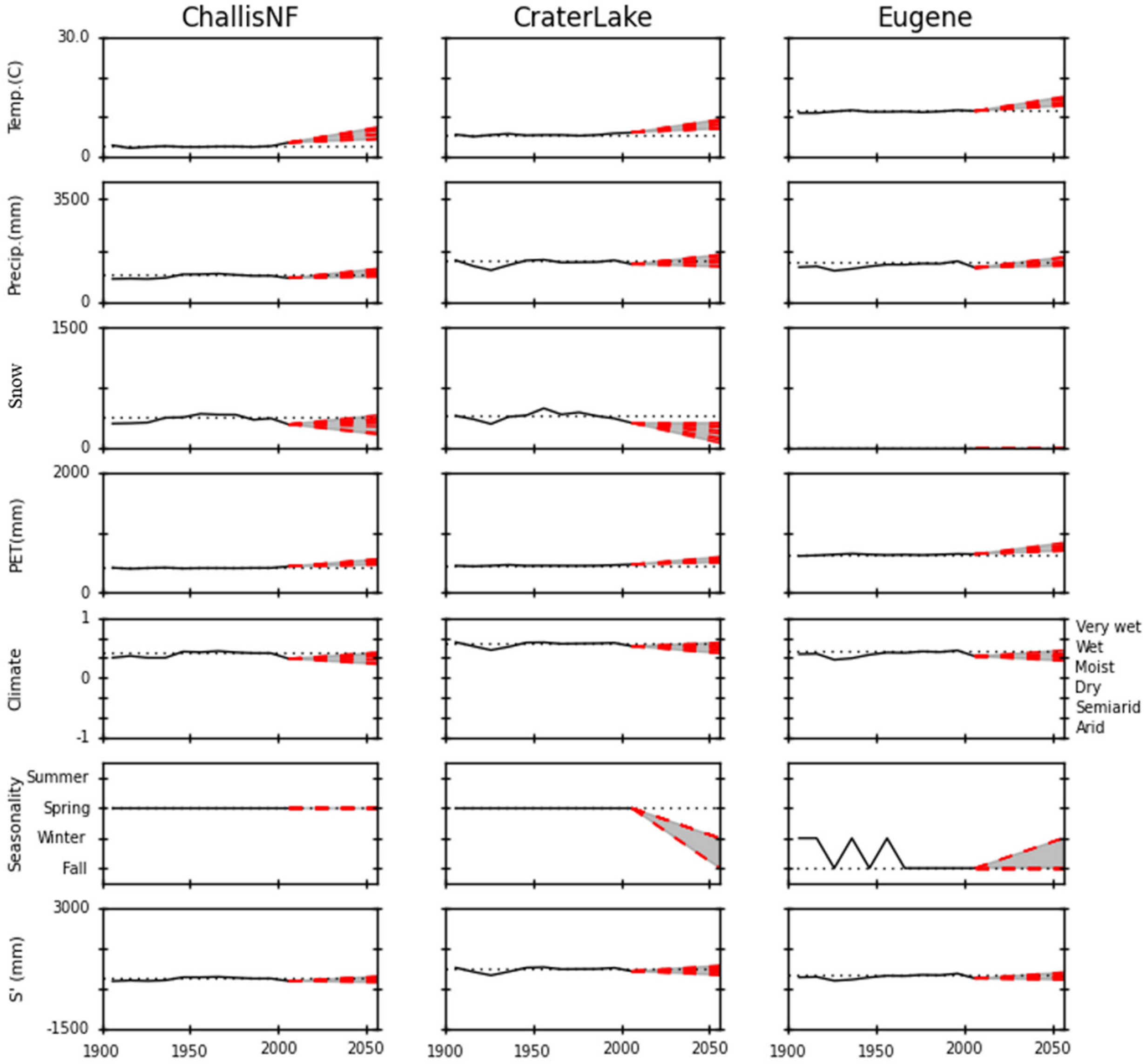


Figure A1. Component Hydrologic Landscape maps of Washington, Idaho, Oregon, California, Nevada, and Arizona were used in the ~~HLVA~~ analysis of the HLVA indices [(a) Subsurface Permeability, (b) Seasonality of precipitation surplus, (c). Surface permeability, (d) Climate, and (e) Terrain]. Notes: The seasonality map for the PNW has been updated from the original Leibowitz et al. 2016 HL map, as we separated their winter seasonality into two seasons (winter and fall).

Figure A2~~ (Plates 1–15)~~

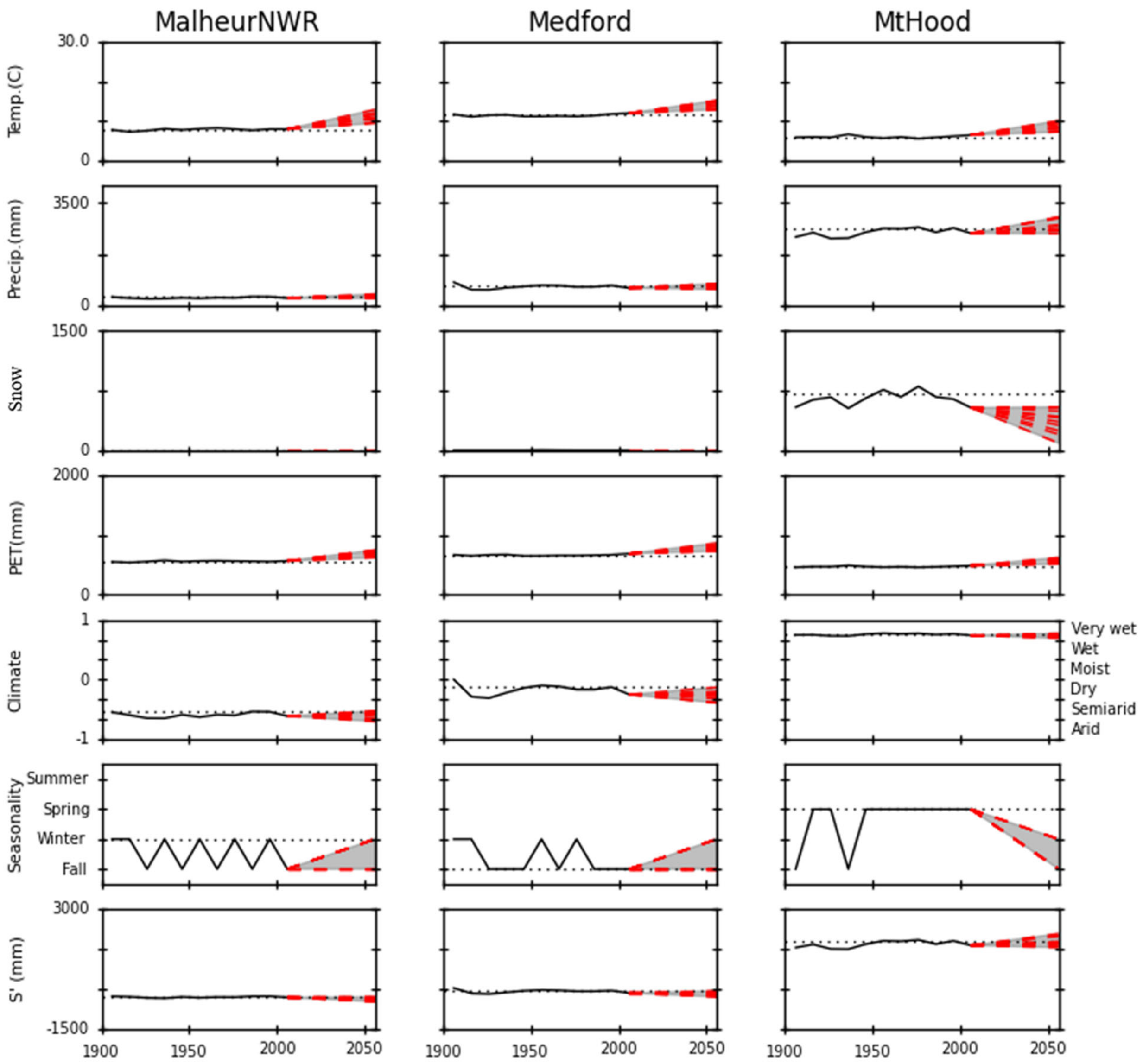
Time series of average decadal temperature, precipitation, snow (April 1 snow water equivalent~~ (mm~~), potential evapotranspiration (PET), climate (FMI), seasonality, and available water (S'~~), FMI, and seasonality)~~ for 45 specific locations ~~identified in Fig. 1 and Table 2 in~~ in the western ~~United States~~U.S. For the climate / FMI figures, the FMI values range from 1 to -1 (primary y-axis on the left), whereas the categorical version of the index ranges from arid to very wet (secondary y-axis on the right). Dotted black line represents the 1971−2000 base period; the dashed red line connects the 2001−2010 value to the 2041−2070 climate projections for each of the ten models. The gray shaded area represents the range of model projections. The number in lower left indicates the HLVA vulnerability index for the metric and location depicted in the associated graph. Note that Oregon, Washington, and Idaho locations are displayed first in alphabetical order and are followed by those of California, Nevada, and Arizona.

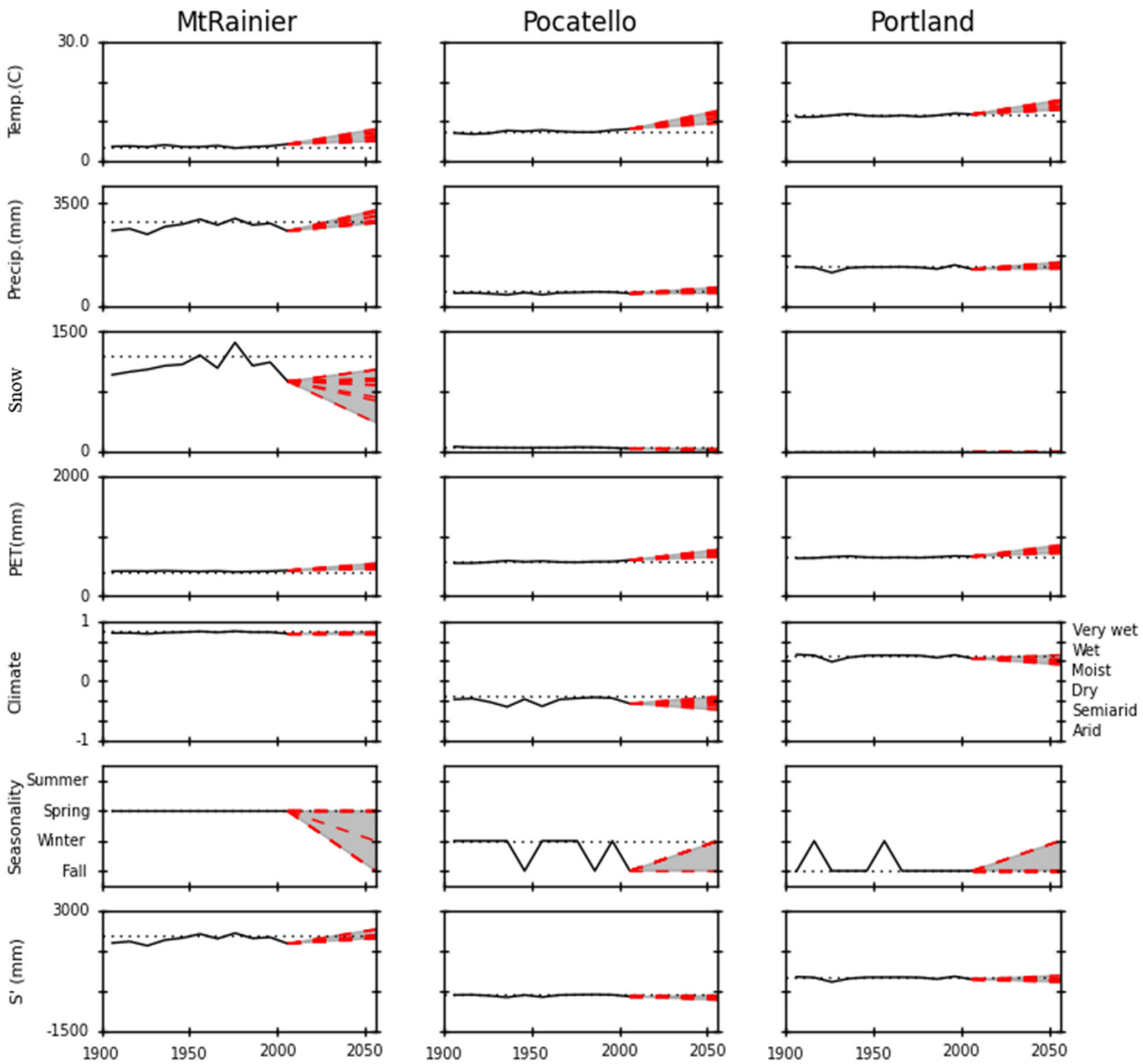


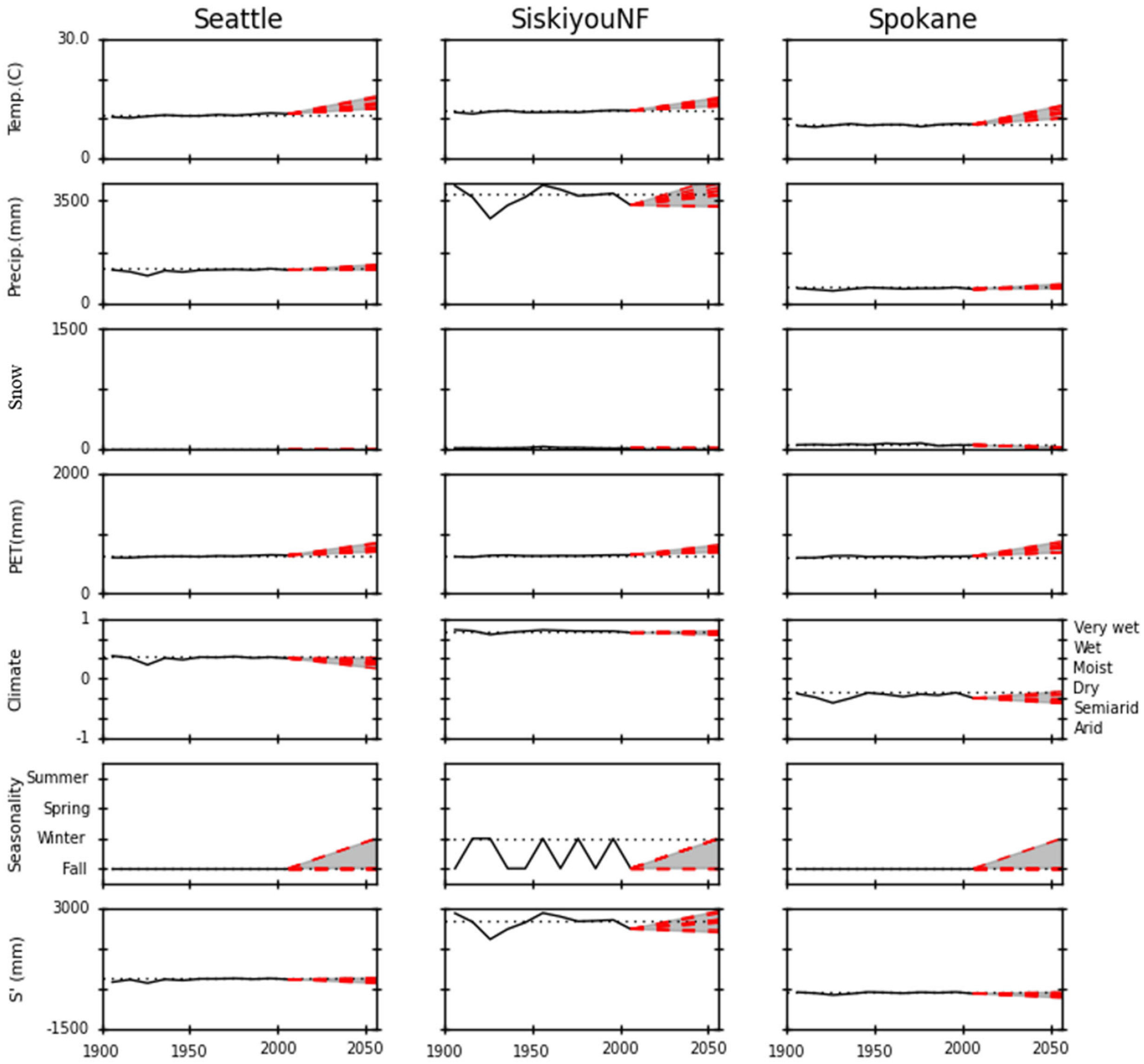


ChallisNF
CraterLake
Eugene
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050

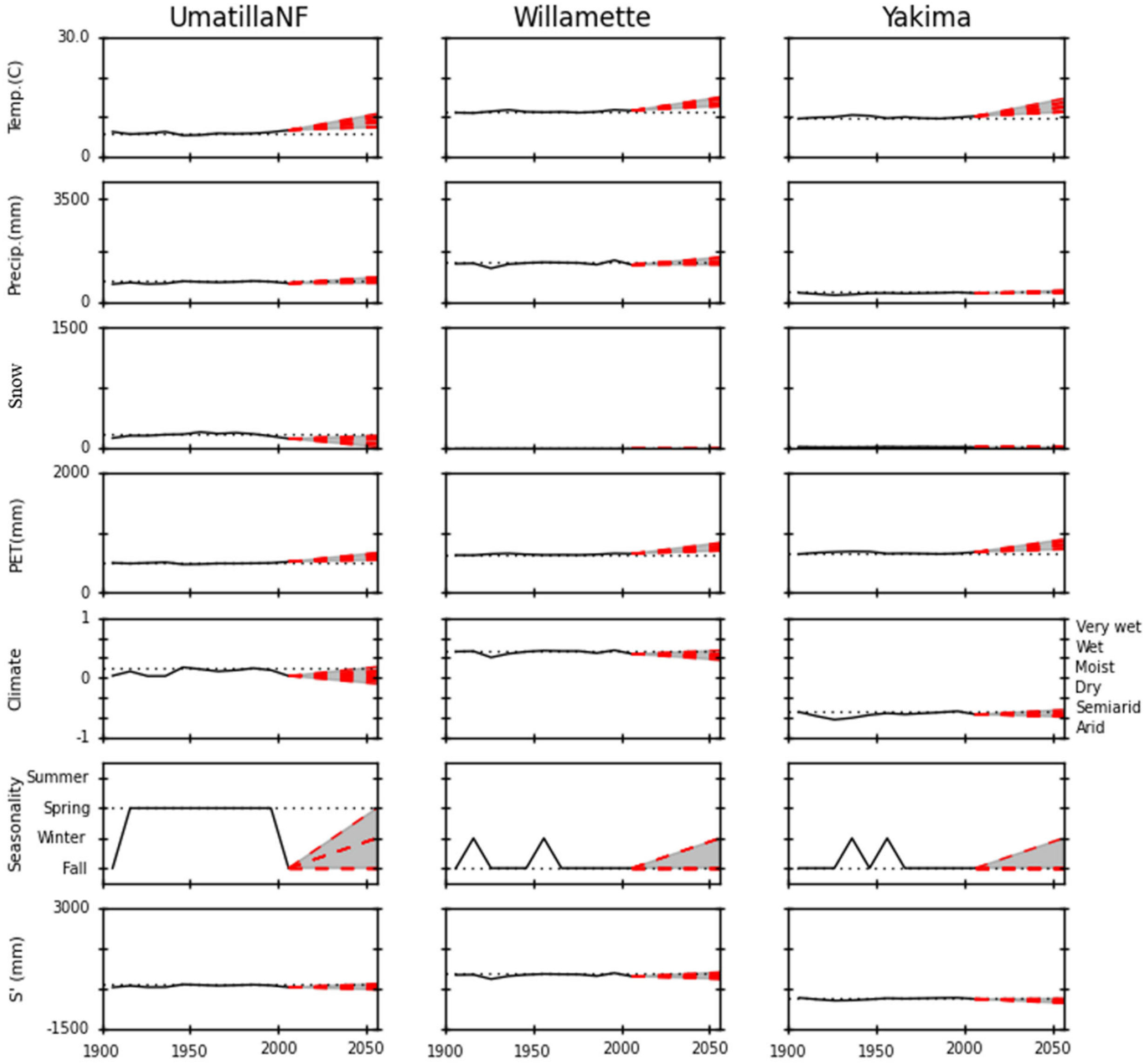
1029

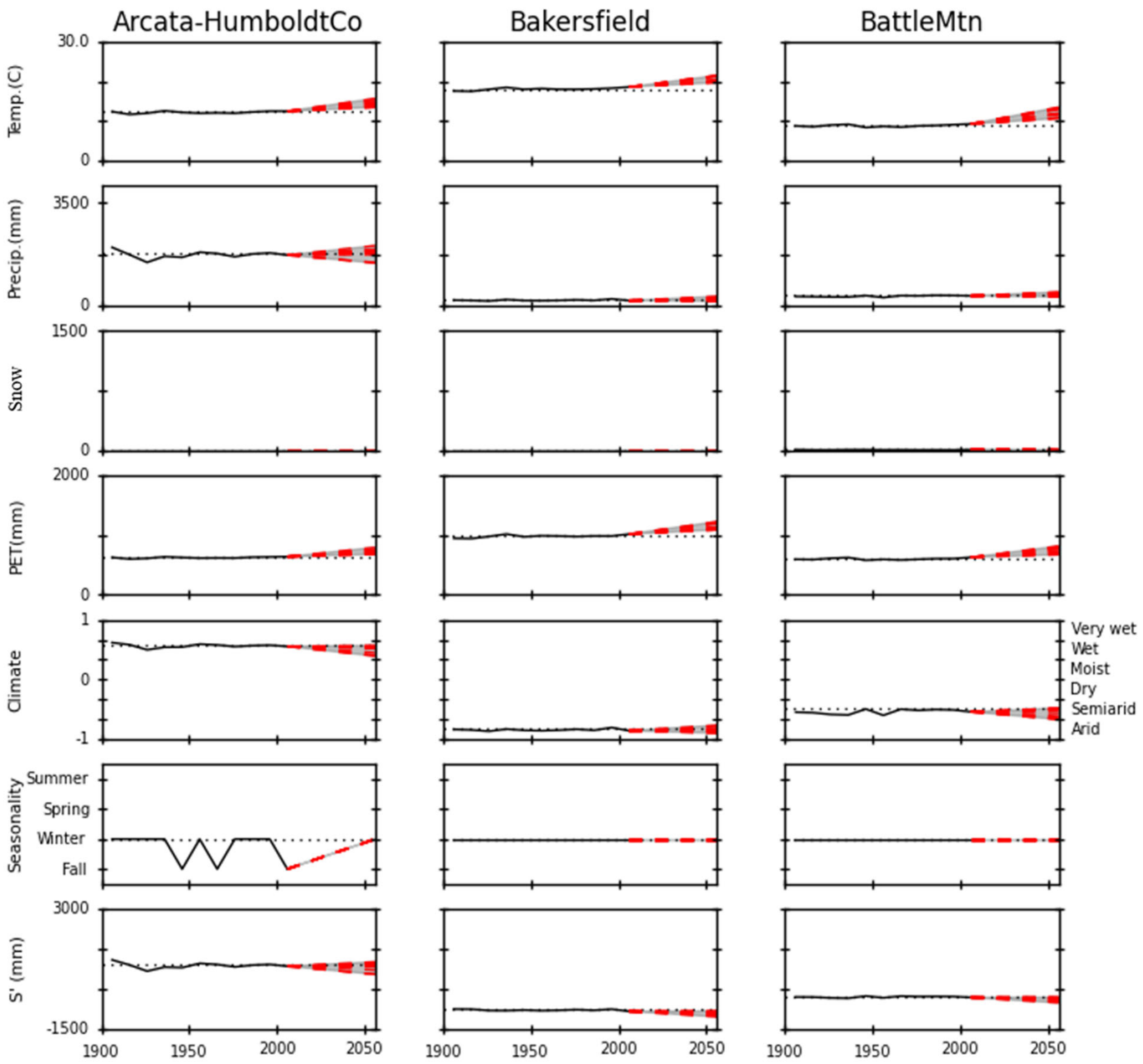

MalheurNWR
Medford
MtHood
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050


MtRainier
Pocatello
Portland
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050



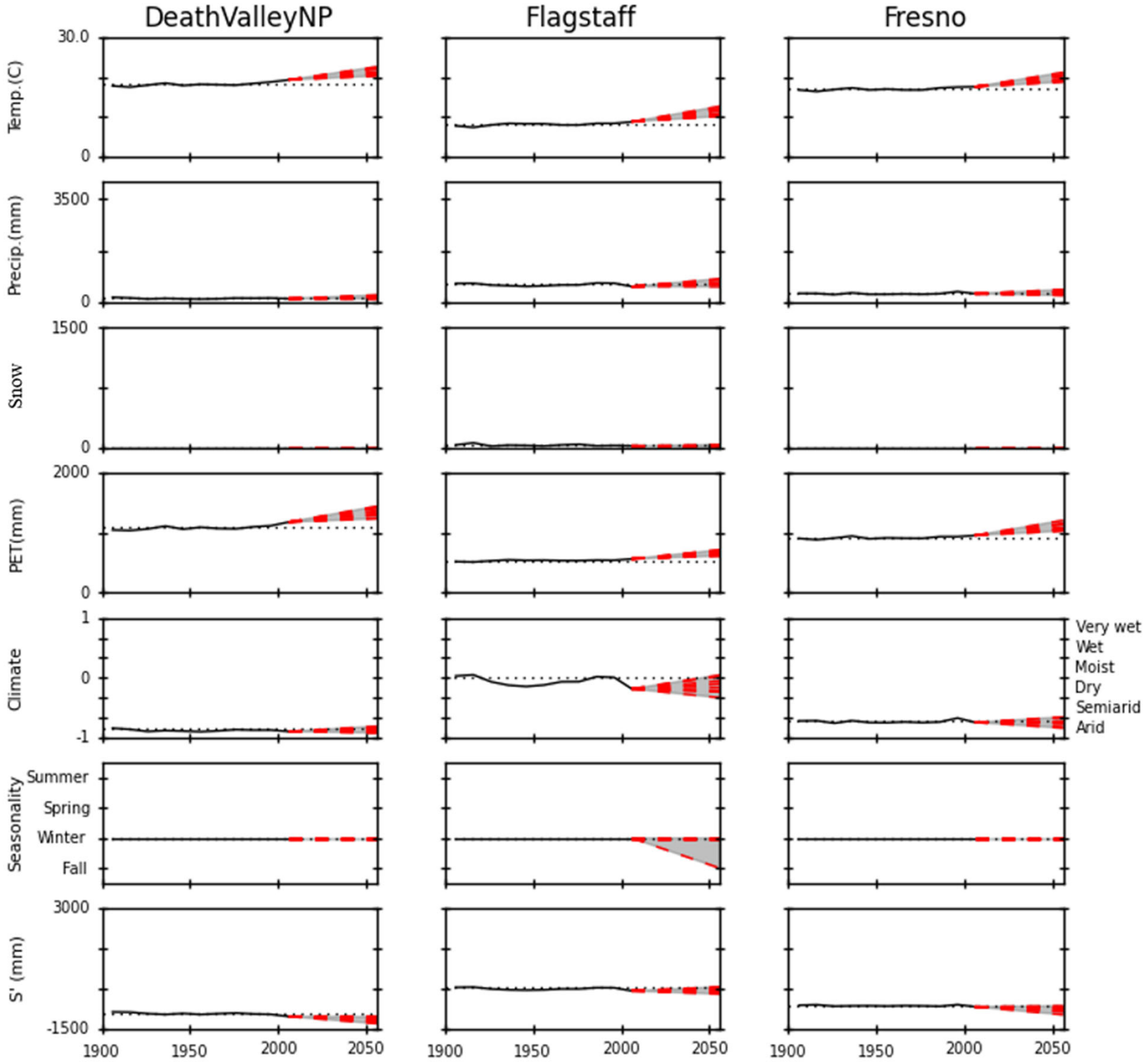
Seattle
SiskiyouNF
Spokane
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050


UmatillaNF
Willamette
Yakima
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050



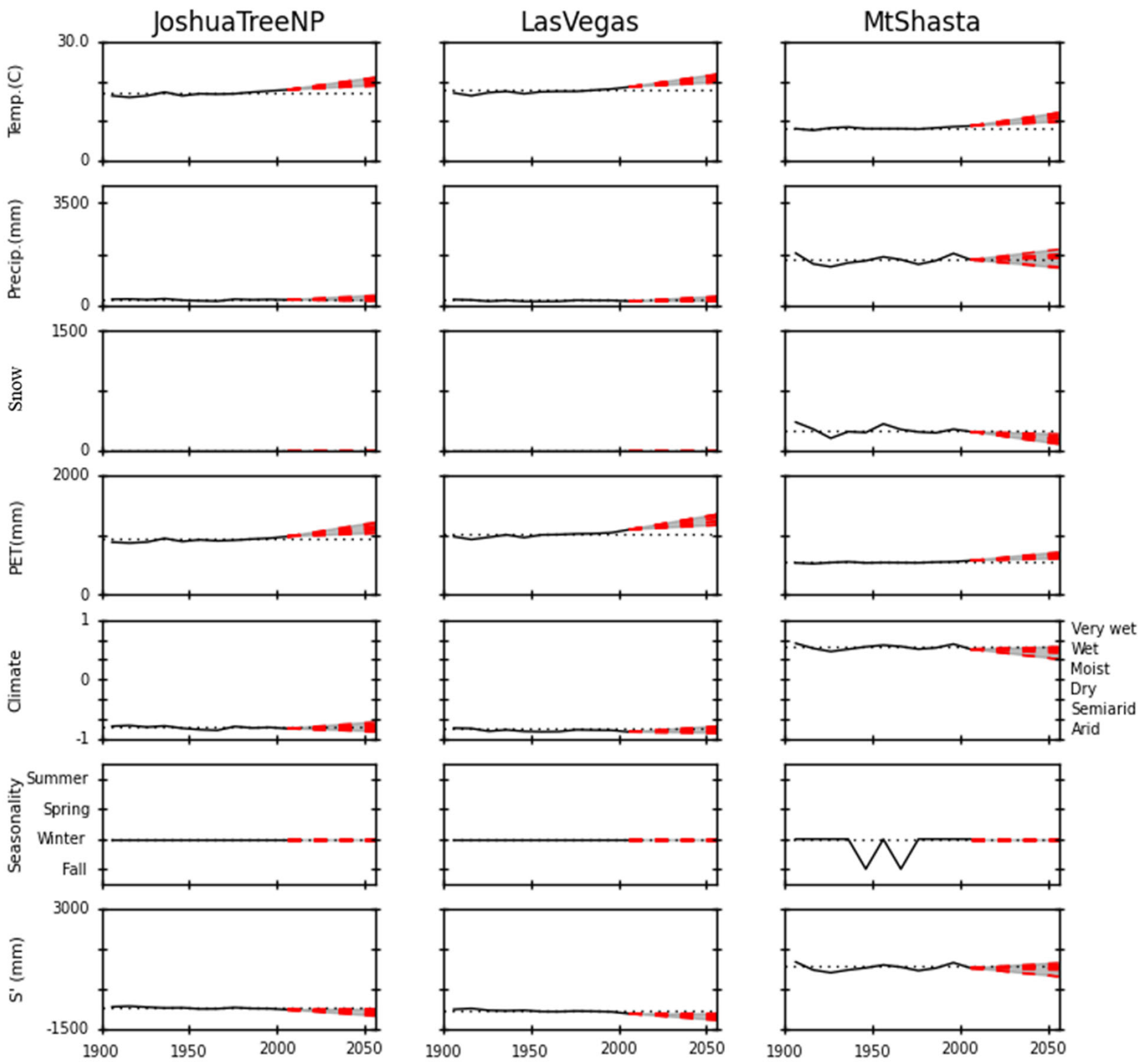
Arcata-HumboldtCo
Bakersfield
BattleMtn
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050

1034

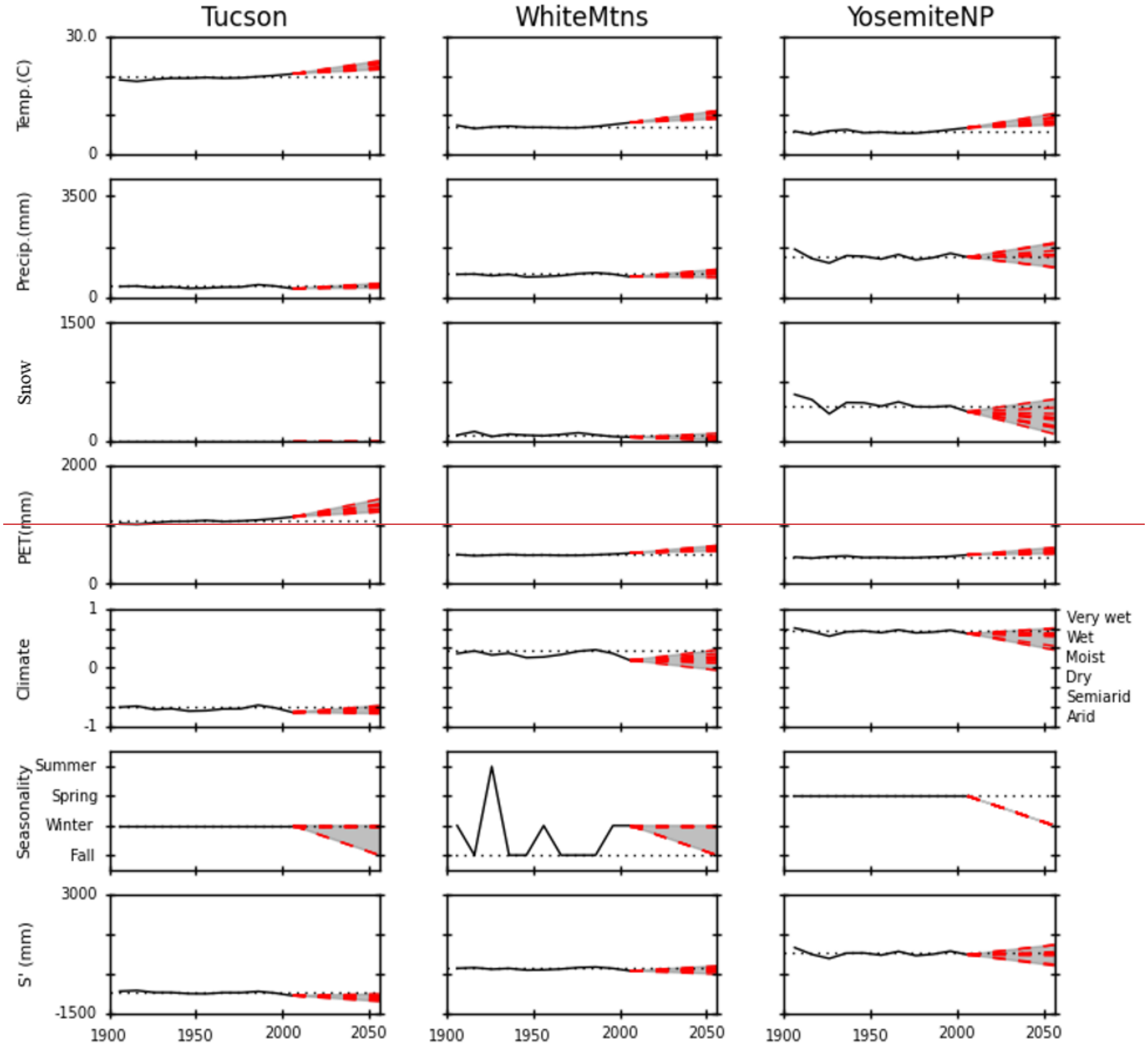

DeathValleyNP
Flagstaff
Fresno
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050

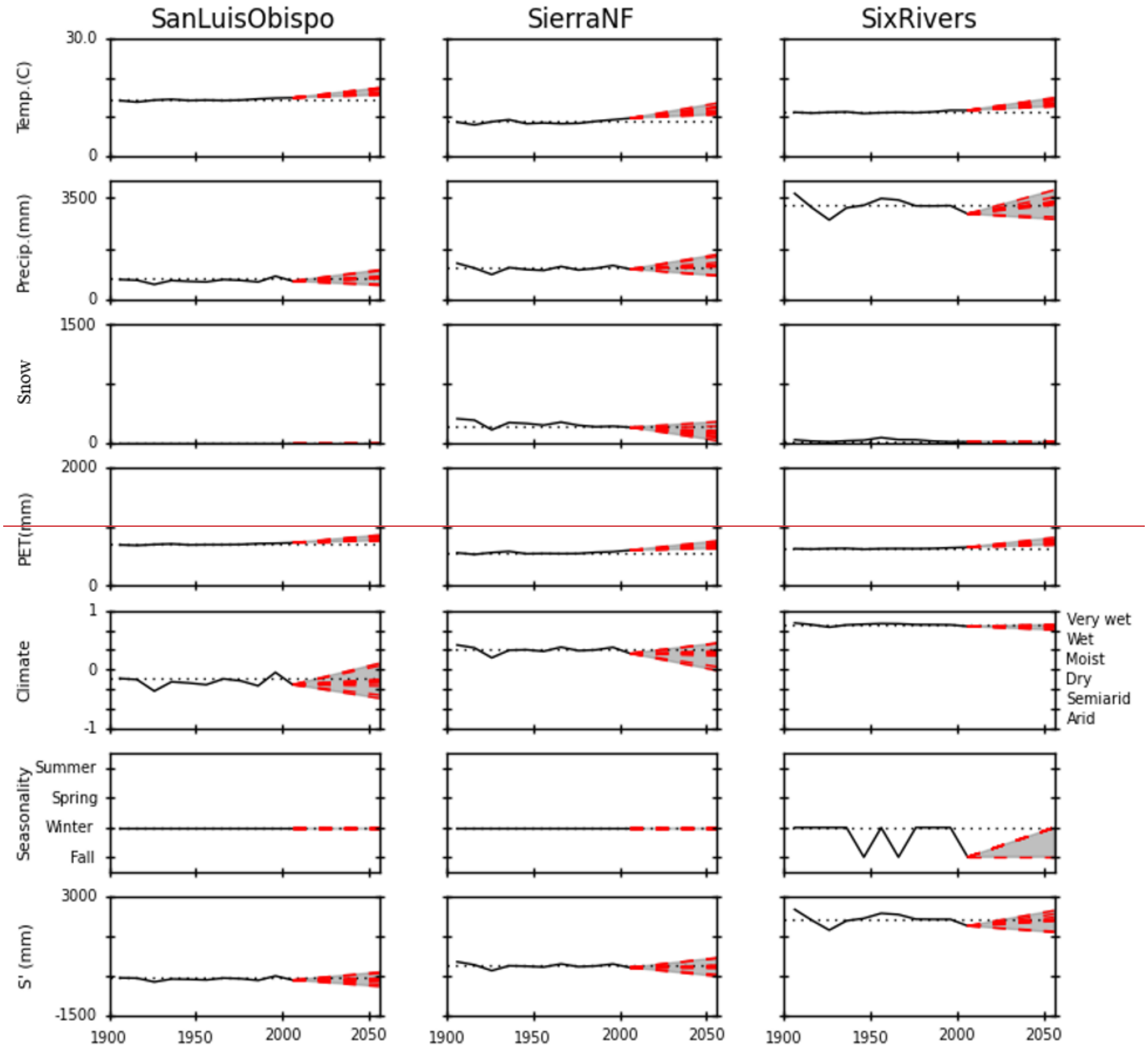
1035

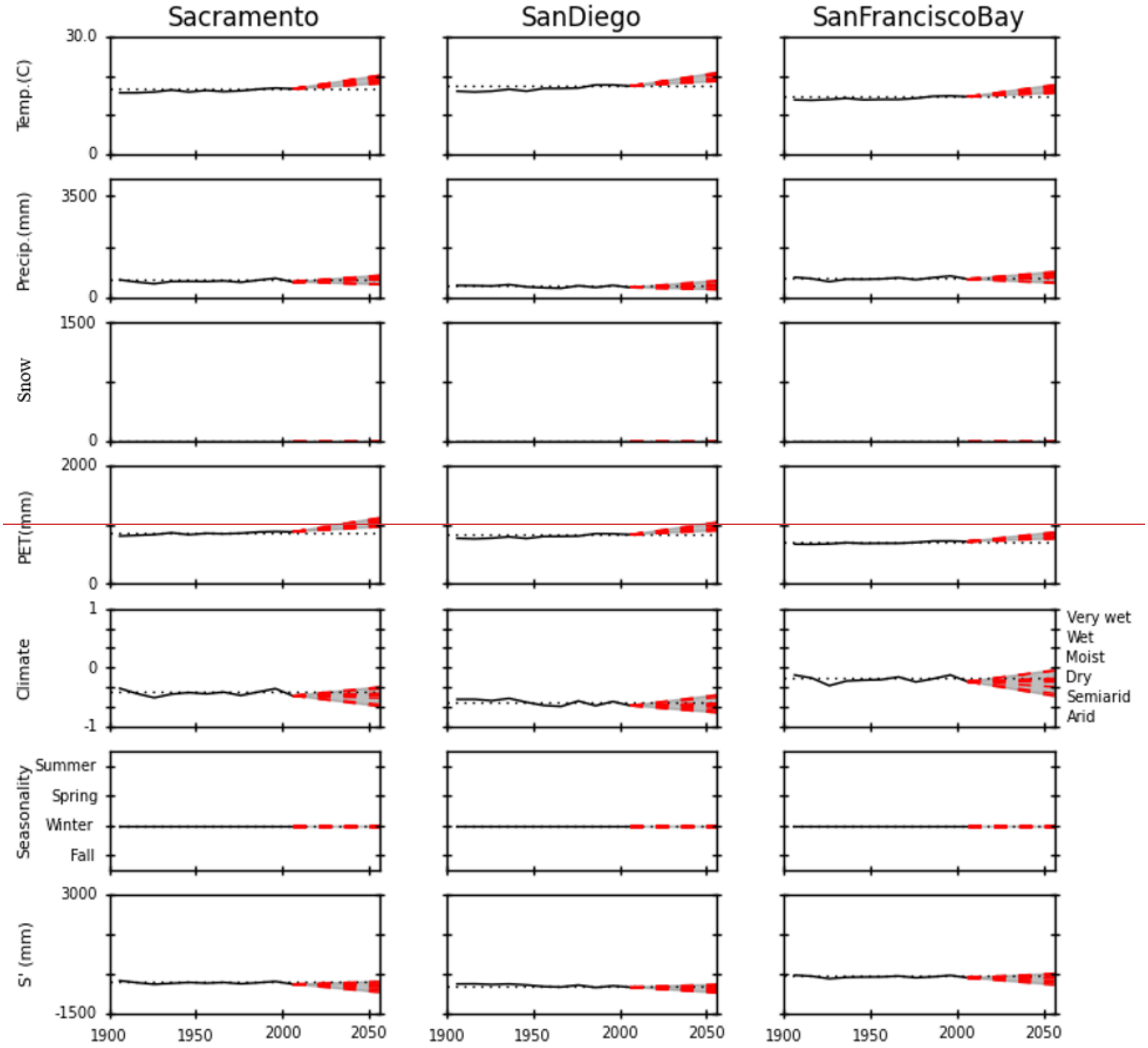
1036



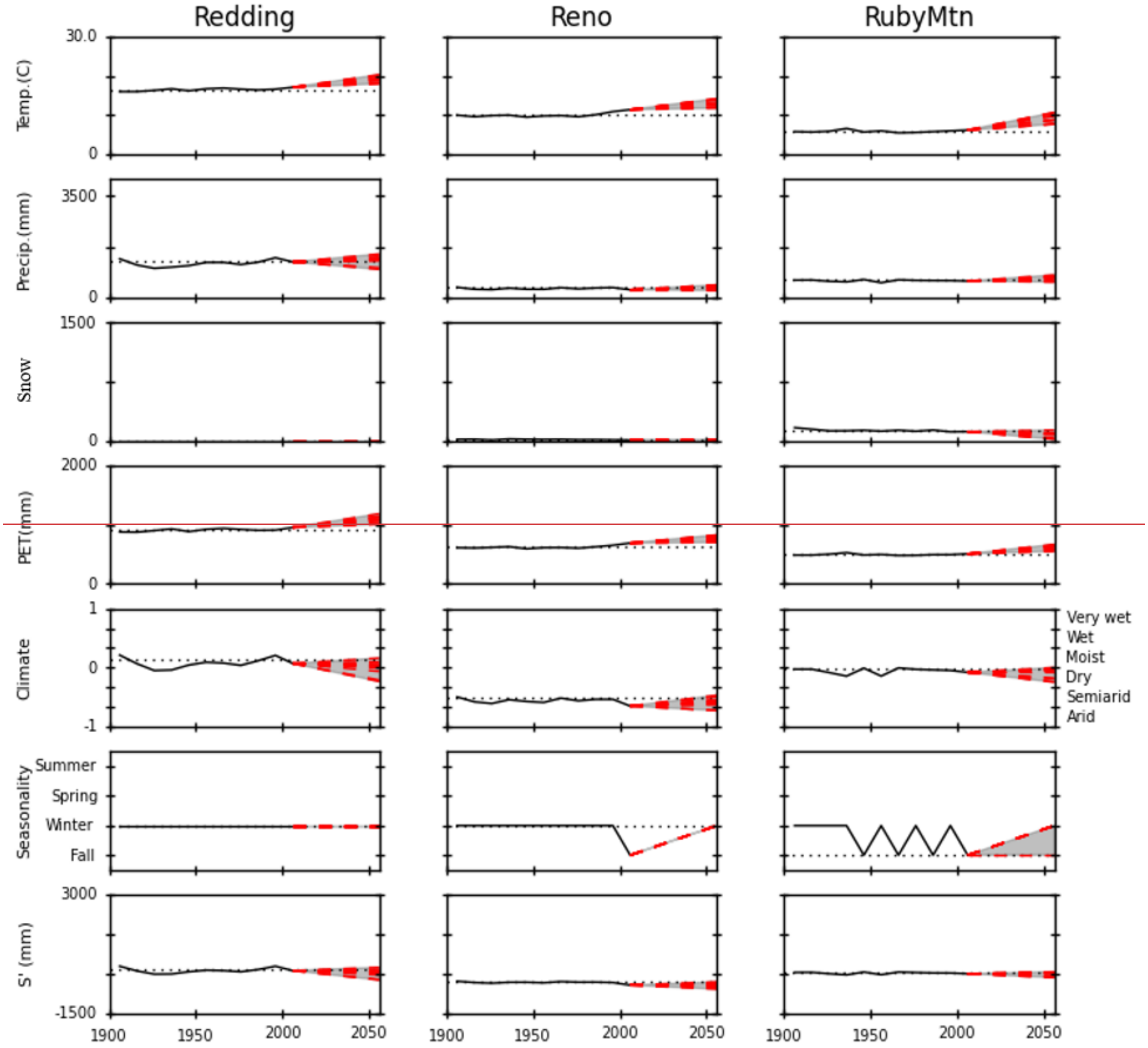
JoshuaTreeNP
LasVegas
MtShasta
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050


Tucson
WhiteMtns
YosemiteNP
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050

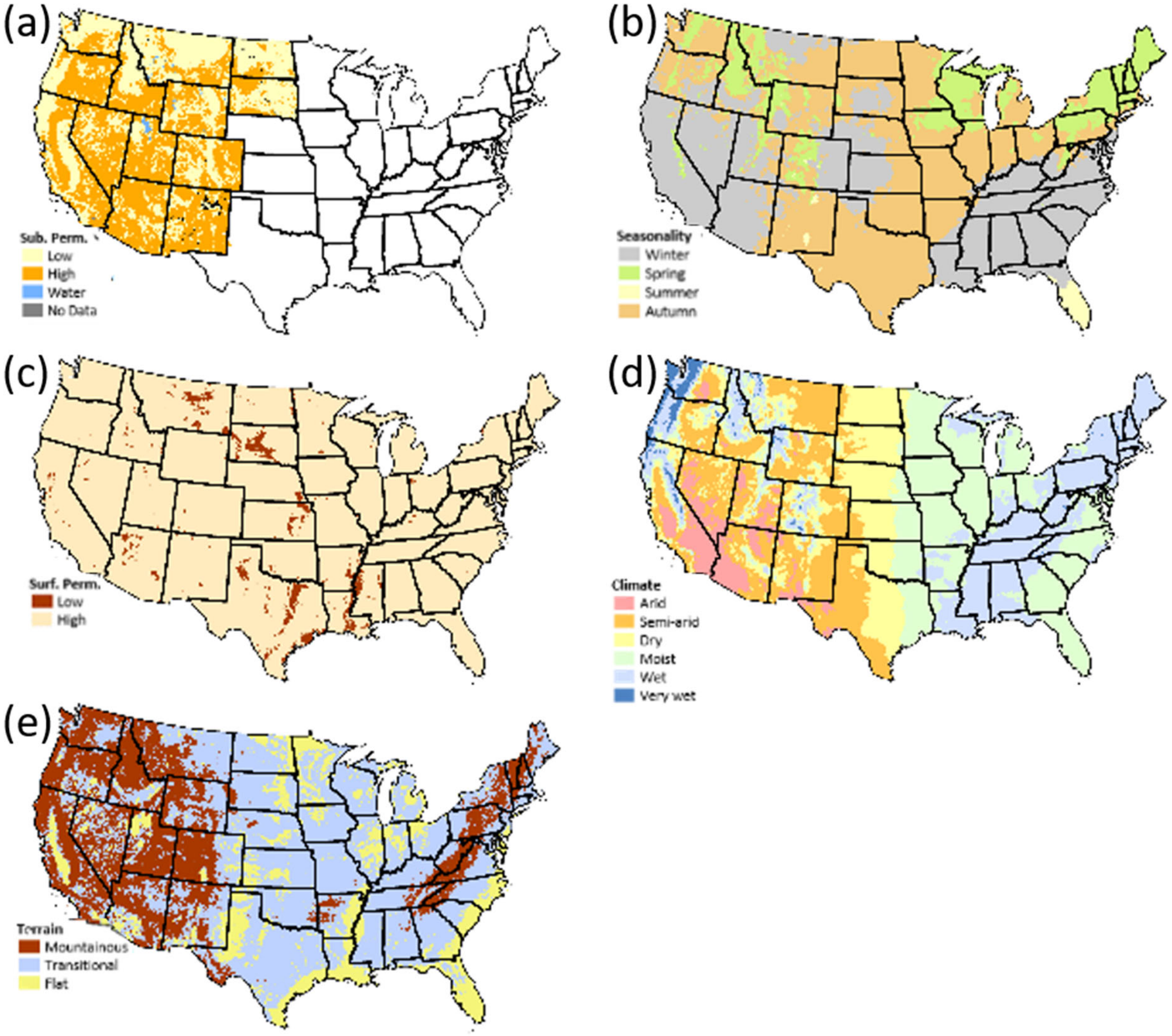

SanLuisObispo
SierraNF
SixRivers
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050


Sacramento
SanDiego
SanFranciscoBay
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050

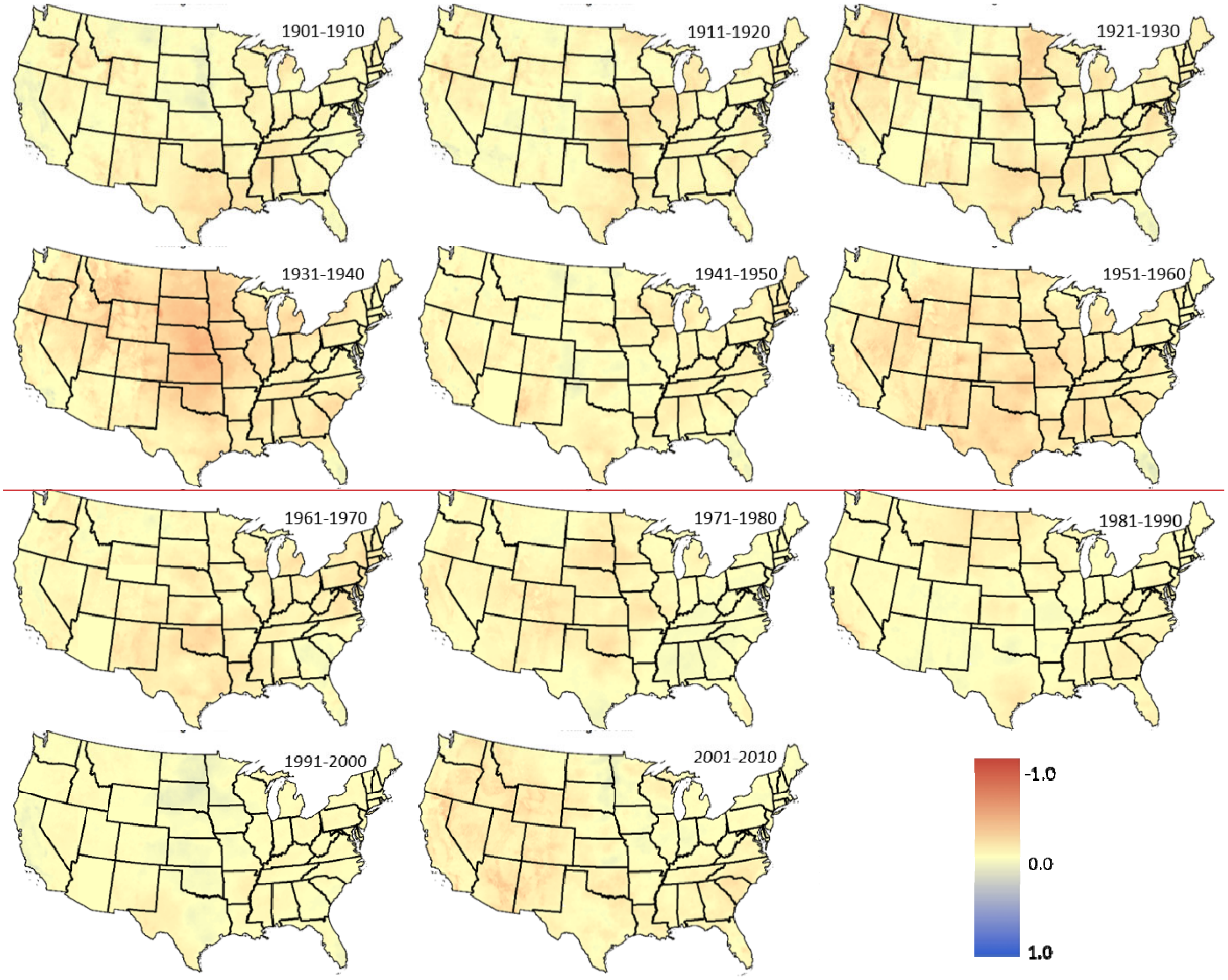
1039


Redding
Reno
RubyMtn
Temp.(C)
30.0
0
Precip.(mm)
3500
0
Snow
1500
0
PET(mm)
2000
0
Climate
1
0
-1
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
S' (mm)
3000
-1500
1900
1950
2000
2050

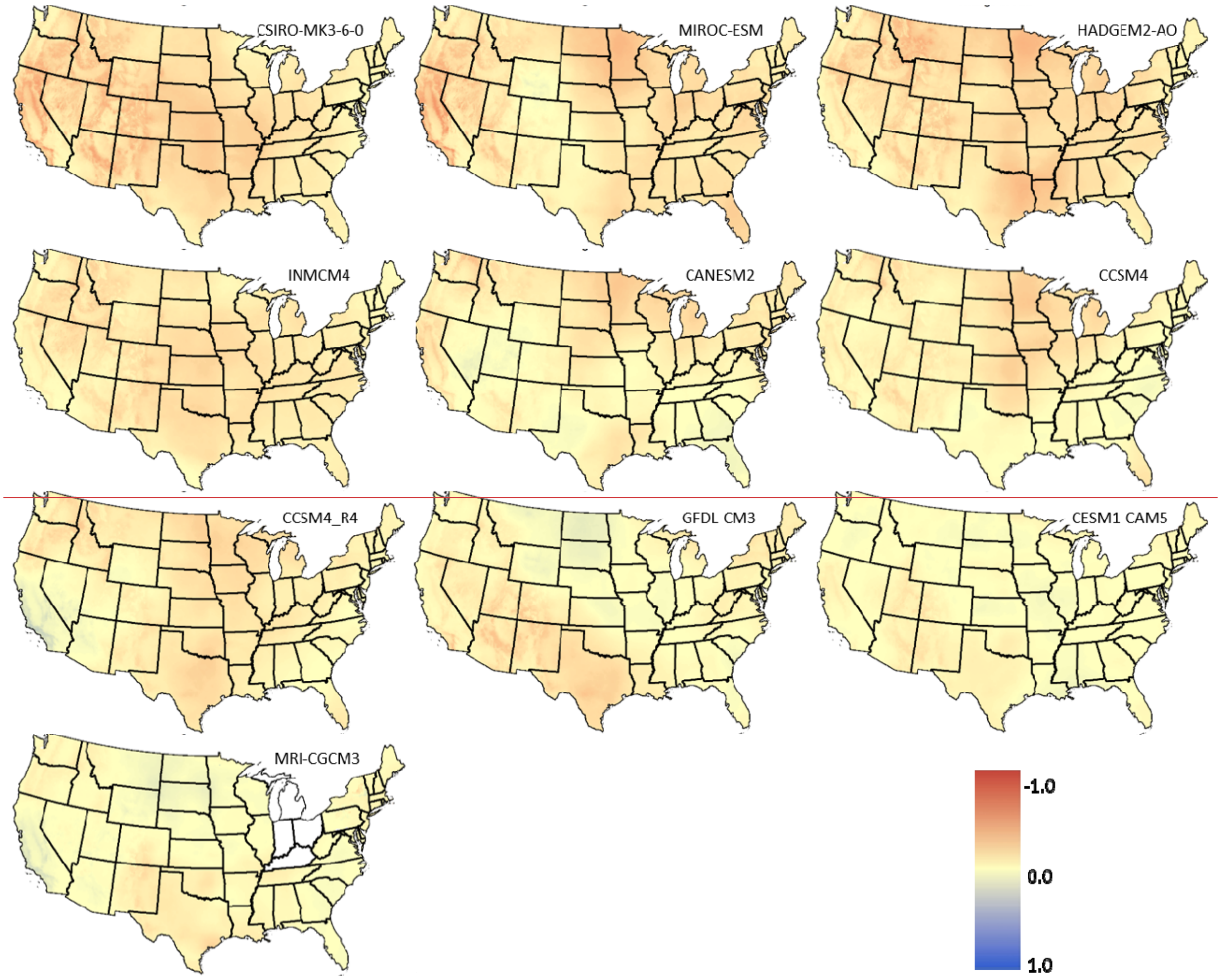
~~Supplemental Material~~



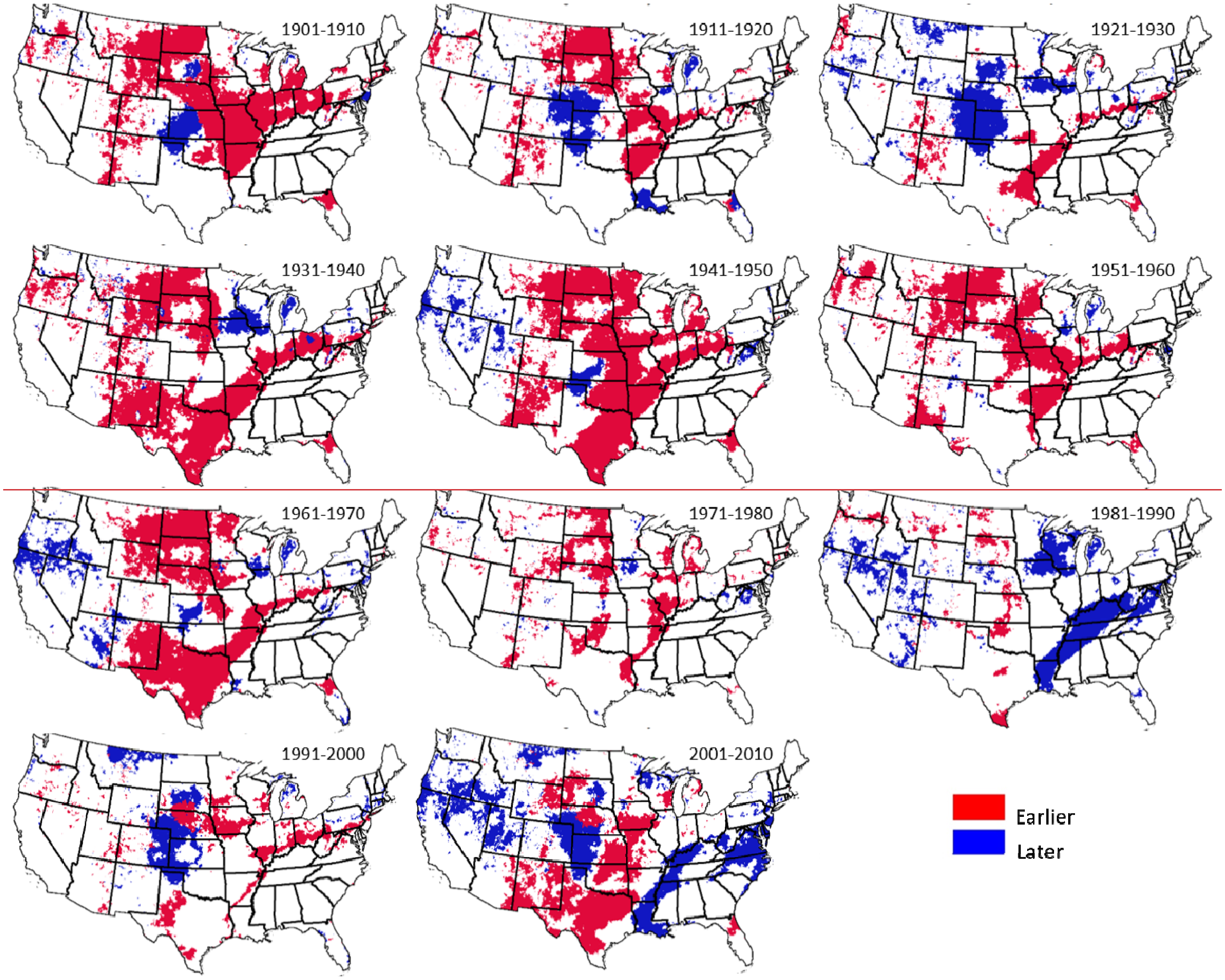
~~Figure S1. Hydrologic Landscape maps of the United States that were used in the HLVA analysis [(a) Subsurface Permeability, (b) Seasonality of precipitation surplus, (c). Surface permeability, (d) Climate, and (e) Terrain]. Notes: The seasonality map for the PNW has been updated from the original Leibowitz 2016 HL map, as we separated their winter seasonality into two seasons (winter and fall). In addition, the subsurface permeability maps were only completed for the western most portions of the U.S.~~



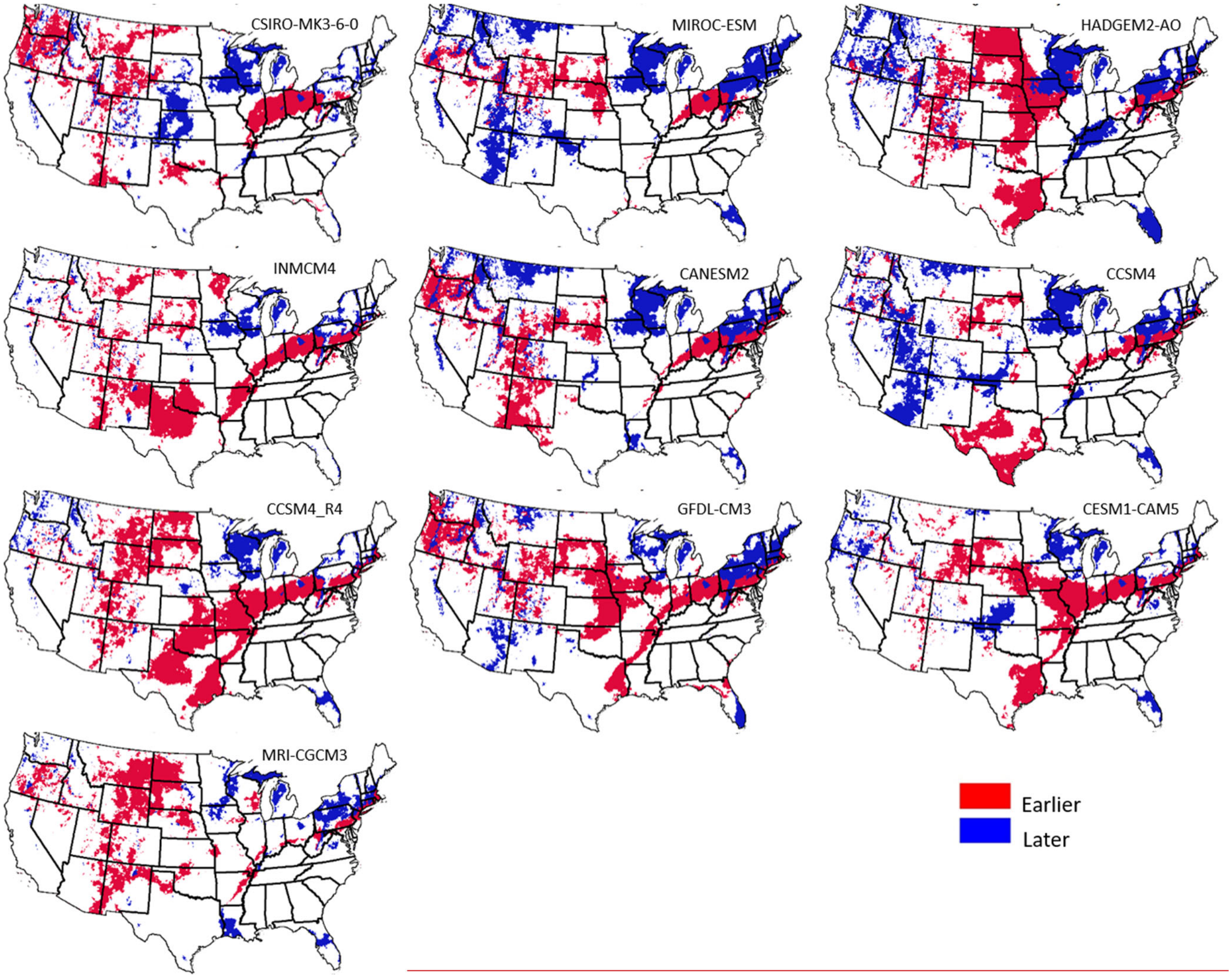
~~**Figure S2. Decadal change in Feddema Moisture Index relative to 1971‒2000 normal period. Red and blue colors indicate drier and wetter average conditions than 1971‒2000, respectively.**~~



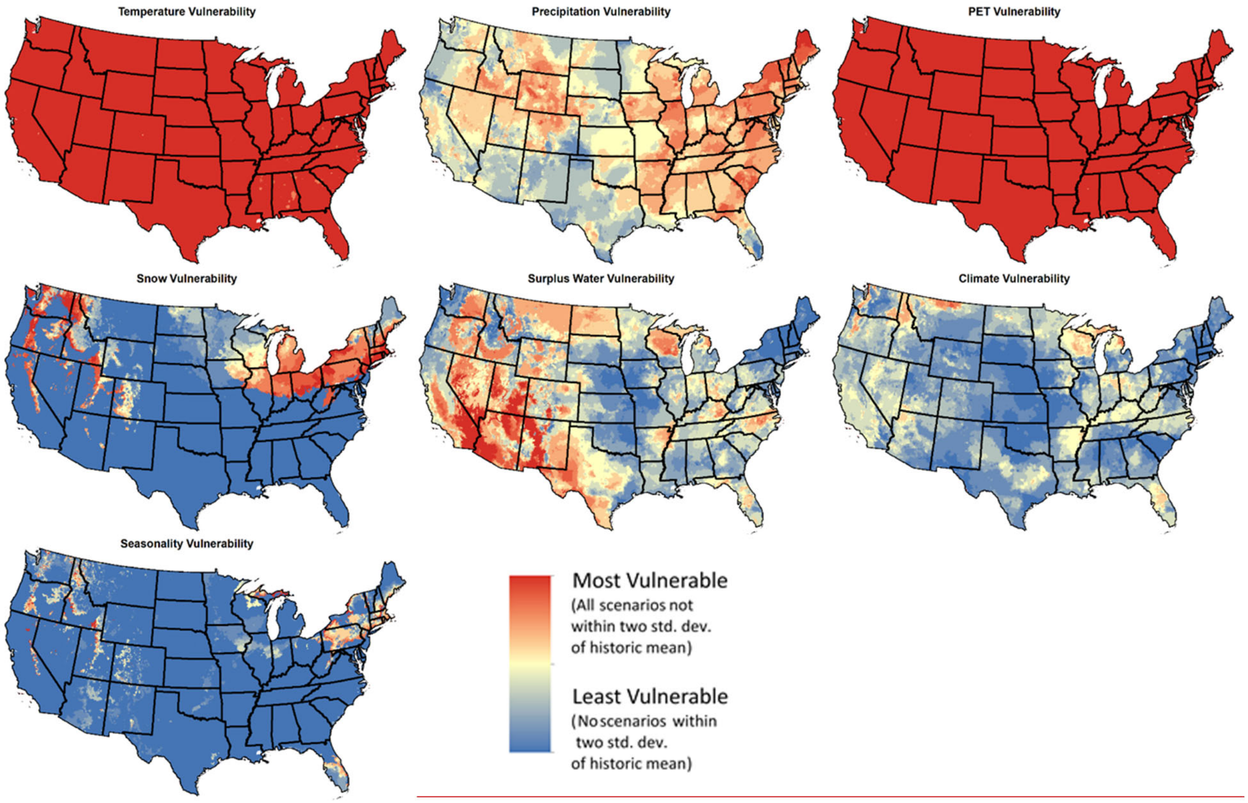
~~Figure S3. Projected change in Feddema Moisture Index for 2041–2070 relative to 1971–2000 for ten climate models. Red and blue colors indicate drier and wetter conditions than the 1971–2000 base period, respectively. Abbreviated model names correlate to those in Table 1.~~



~~Figure S4. Decadal change in seasonality of water surplus since 1901 relative to 1971–2000. Red and blue colors indicate earlier and later seasonality than the 1971–2000 base period, respectively.~~

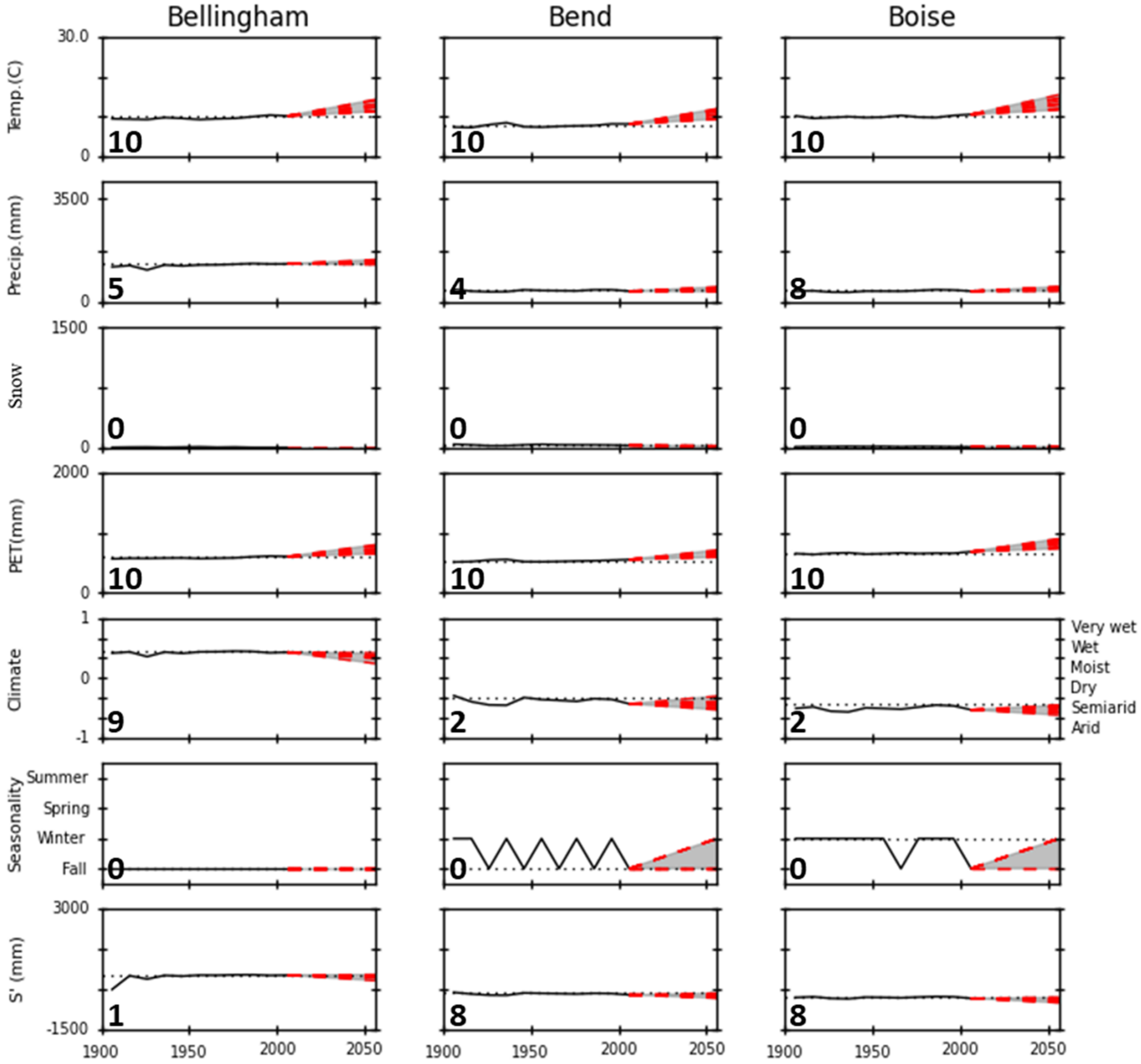


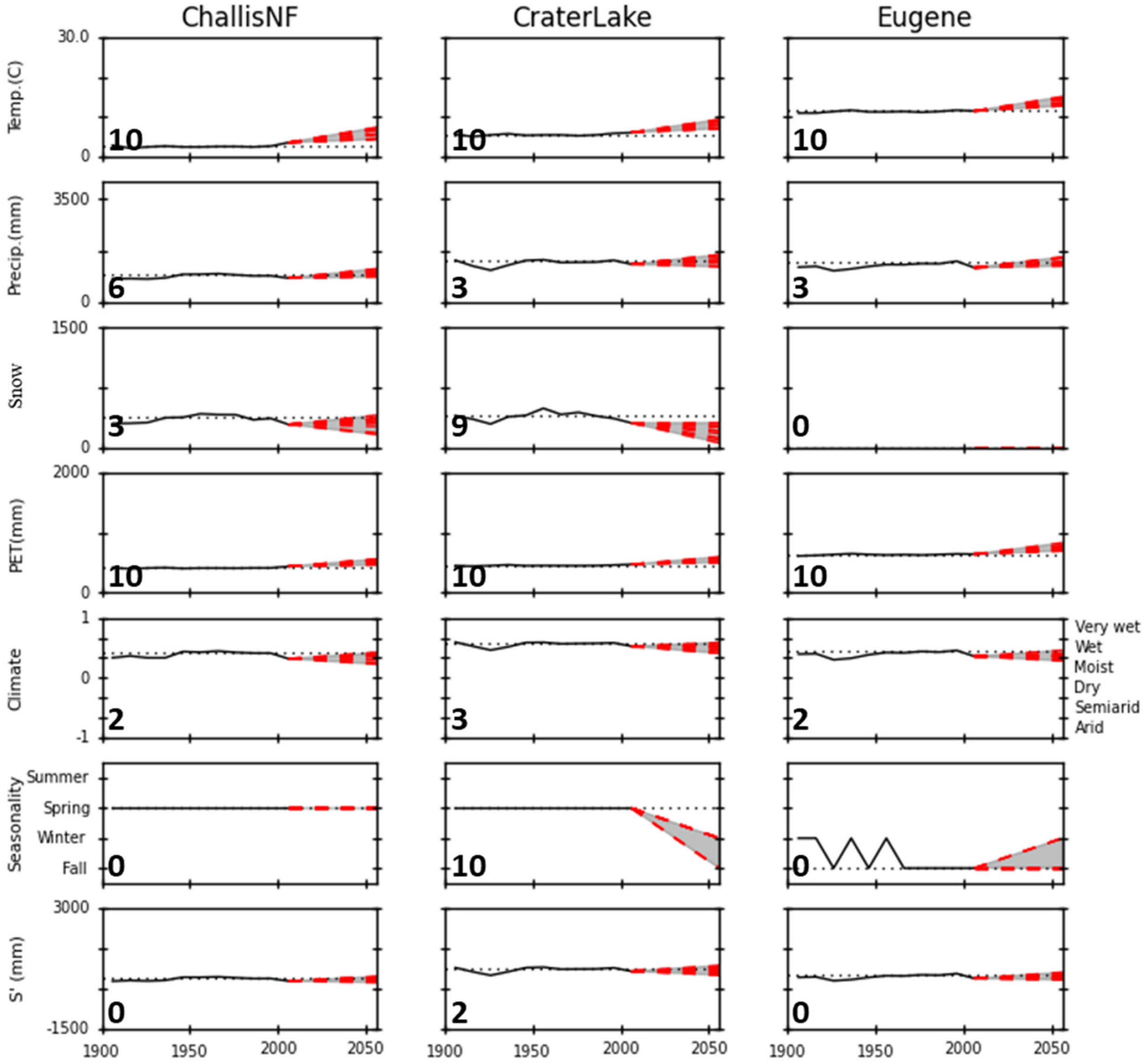
~~**Figure S5. Projected change in seasonality of water surplus for 2041–2070 relative to 1971–2000 for ten climate models. Red and blue colors indicate earlier and later seasonality than the 1971–2000 base period, respectively. Abbreviated model names correlate to those in Table 1.**~~

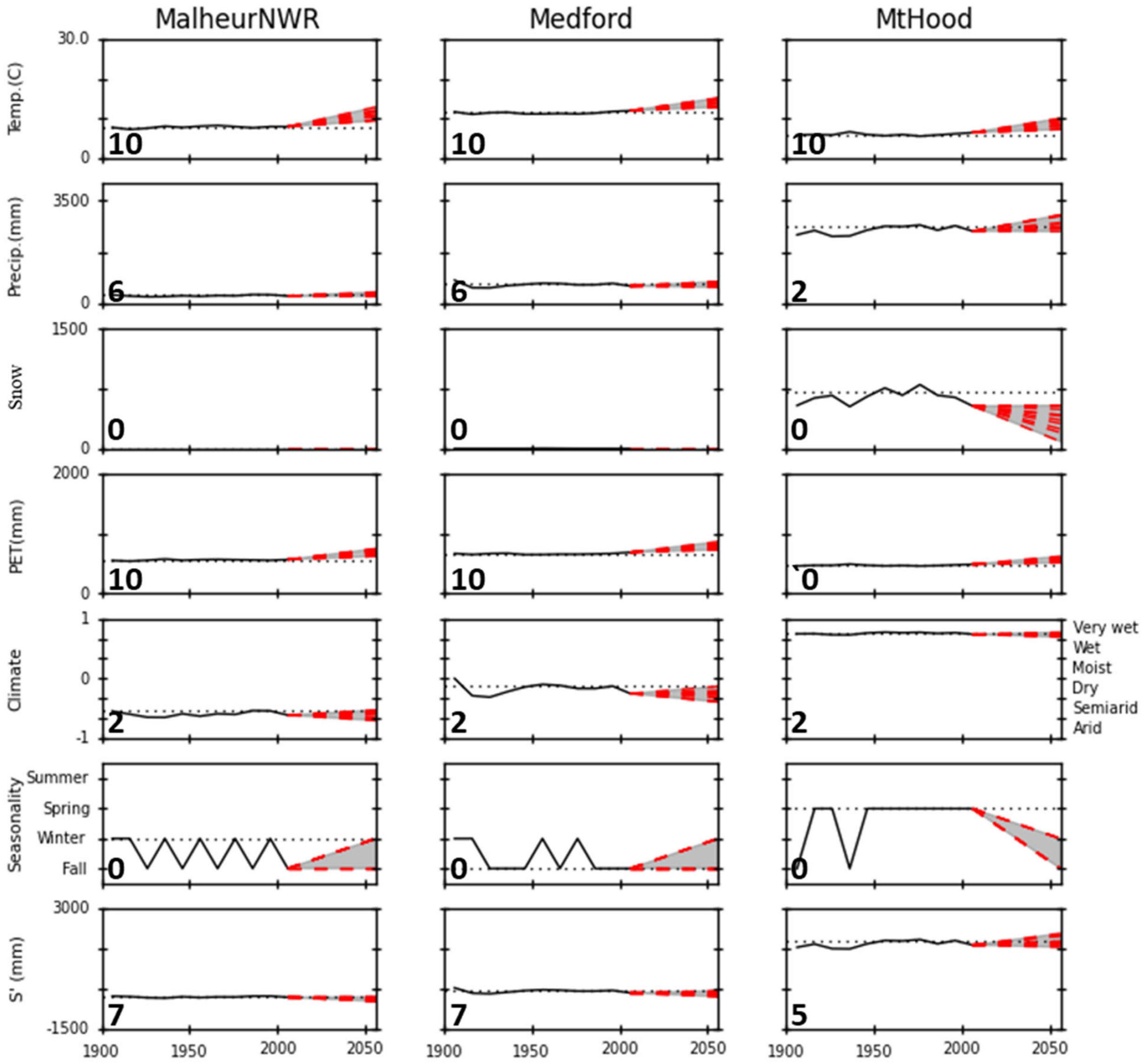


~~**Figure S6. Vulnerability indices for temperature, precipitation, potential evapotranspiration, snow water equivalent (April 1), S' (available water), Feddema Moisture Index, and seasonality. The least vulnerable locations are those projected to be**~~

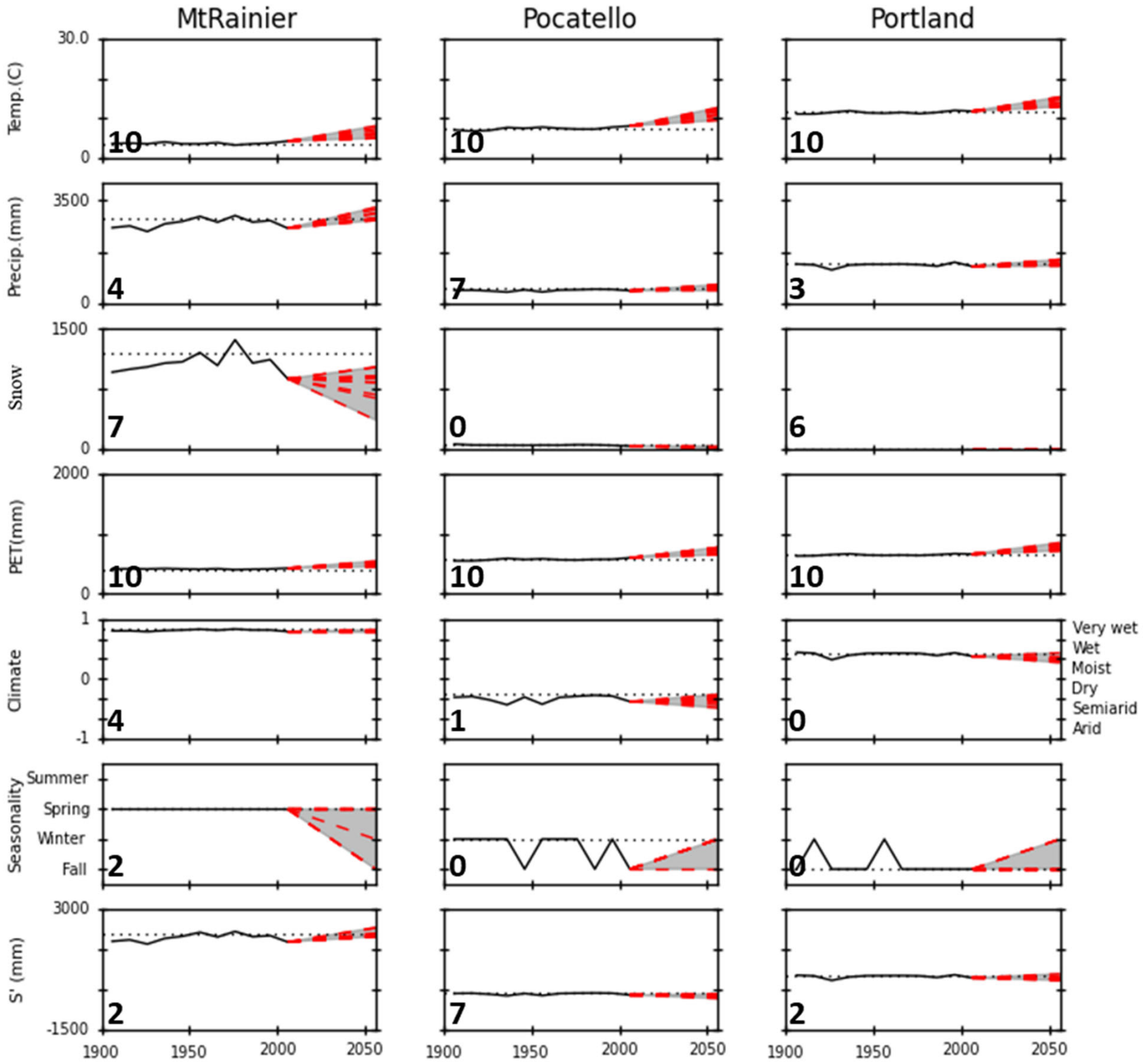
~~within two-standard deviations of the historic (1901-201) mean in all nine climate models.~~

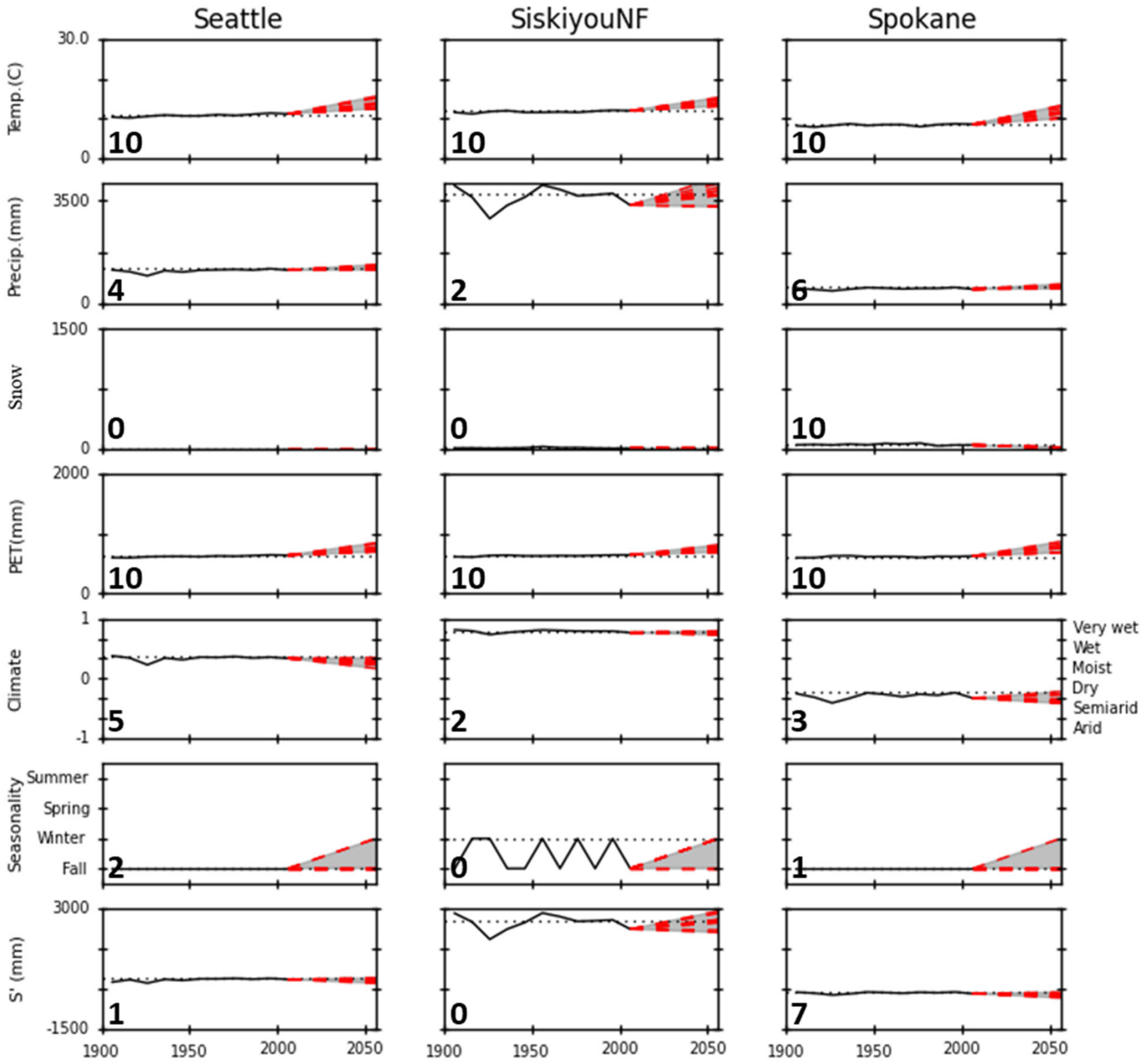


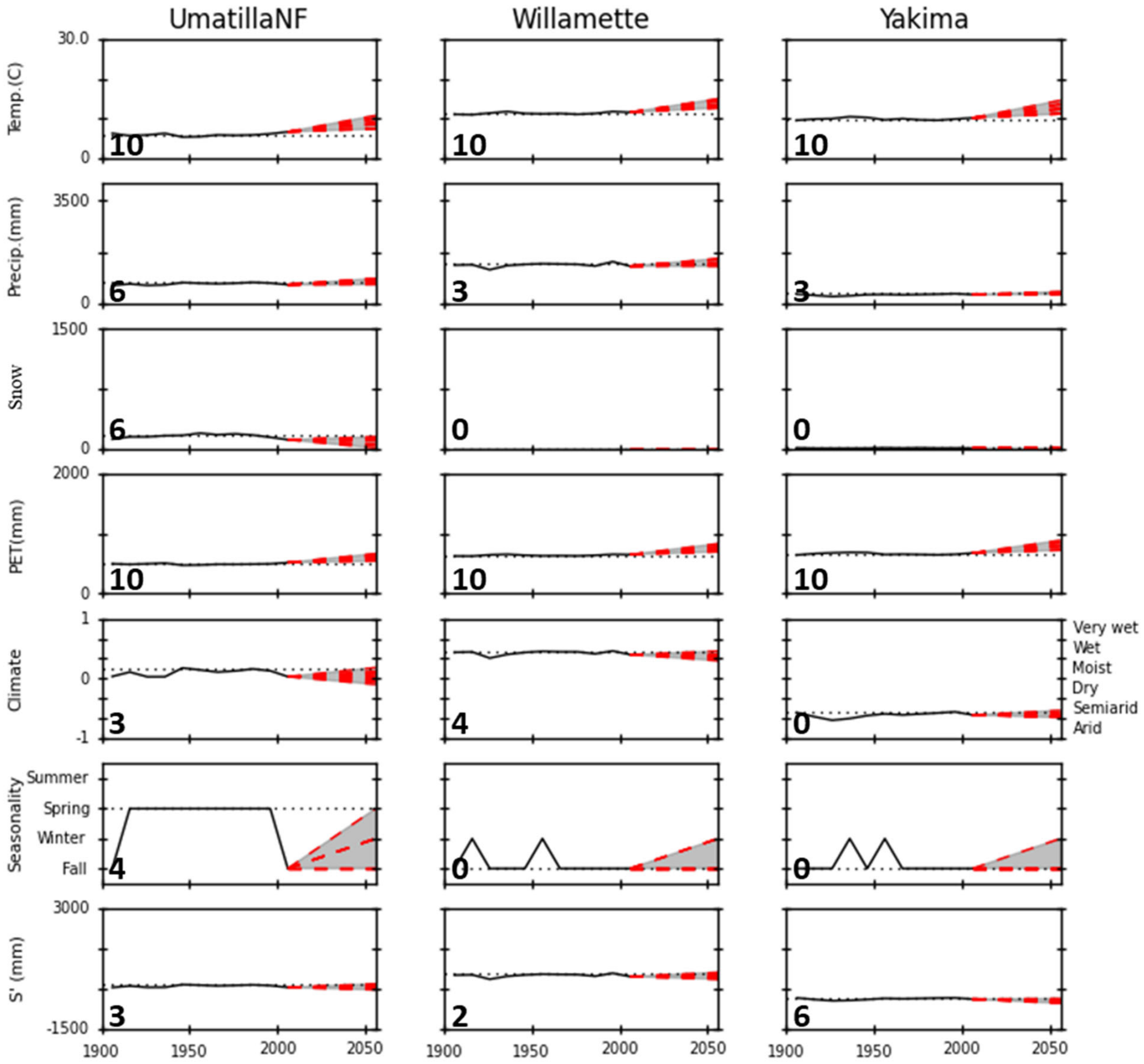

ChallisNF
CraterLake
Eugene
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
6
3
3
Snow
1500
0
3
9
0
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
2
3
2
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
10
0
S' (mm)
3000
-1500
0
2
0
1900
1950
2000
2050
1900
1950
2000
2050
1900
1950
2000
2050

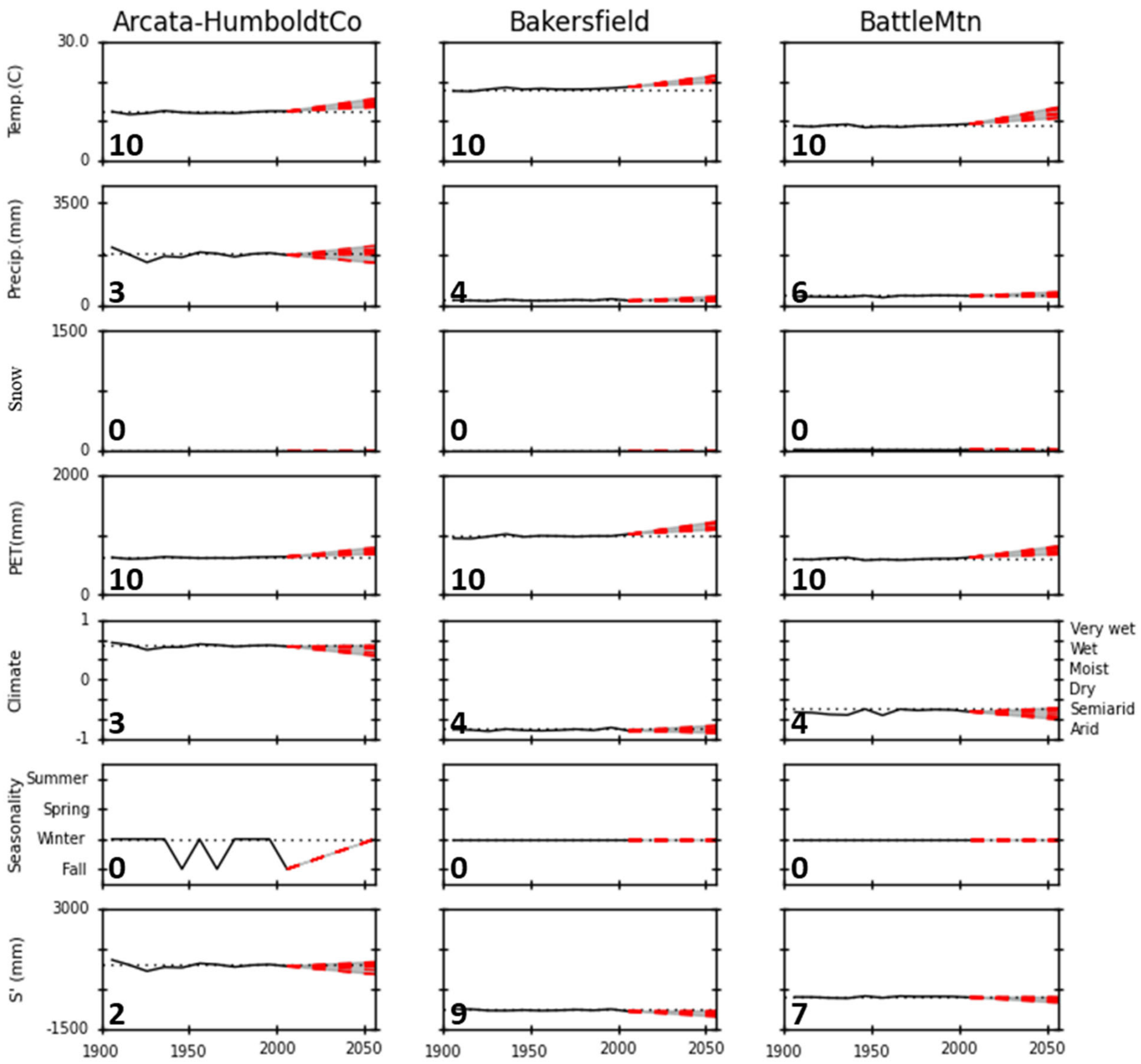


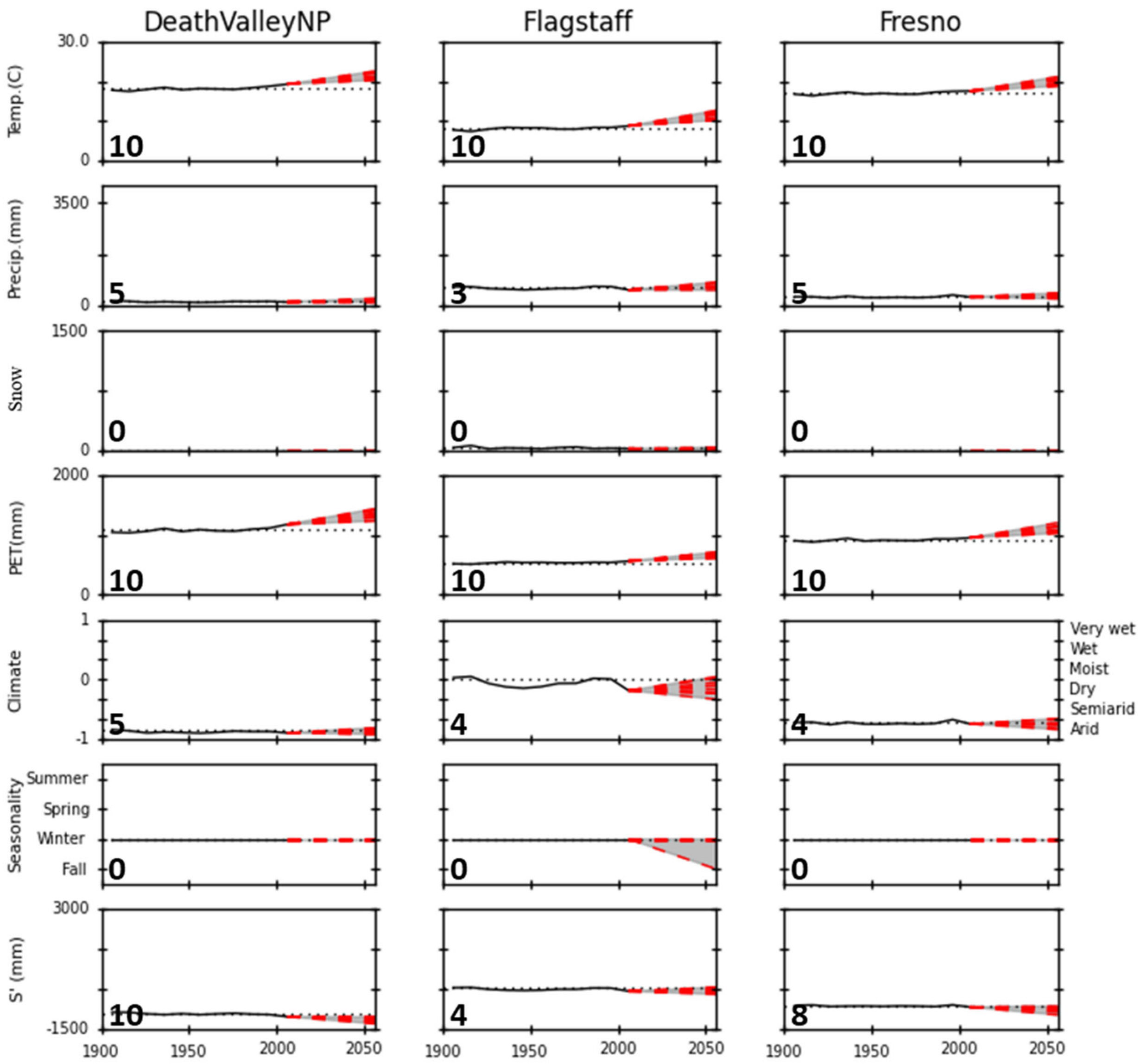
MalheurNWR
Medford
MtHood
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
6
6
2
Snow
1500
0
0
0
0
PET(mm)
2000
0
10
10
0
Climate
1
0
-1
2
2
2
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
0
0
S' (mm)
3000
-1500
7
7
5
1900
1950
2000
2050

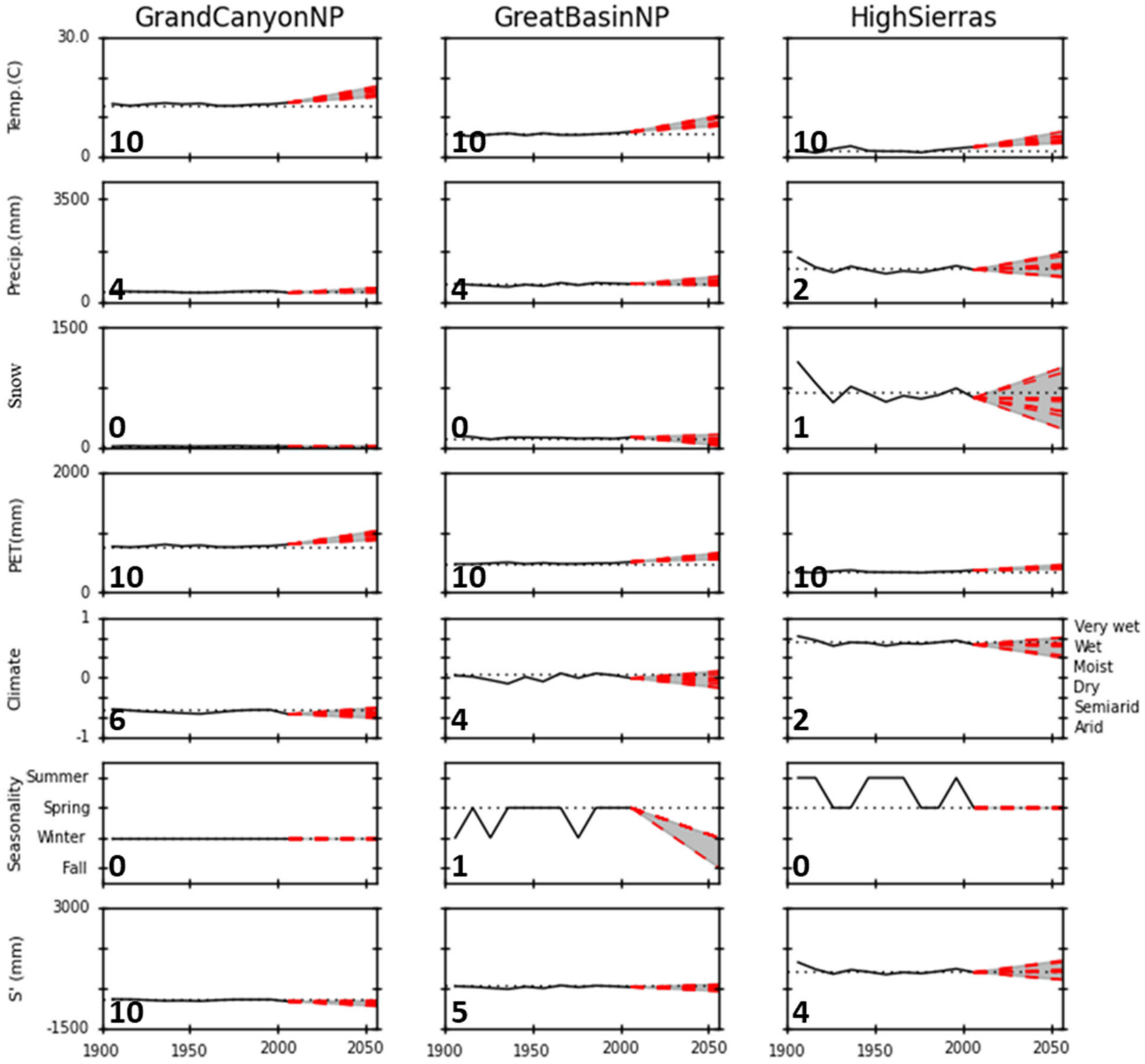

MtRainier
Pocatello
Portland
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
4
7
3
Snow
1500
0
7
0
6
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
4
1
0
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
2
0
0
S' (mm)
3000
-1500
2
7
2
1900
1950
2000
2050

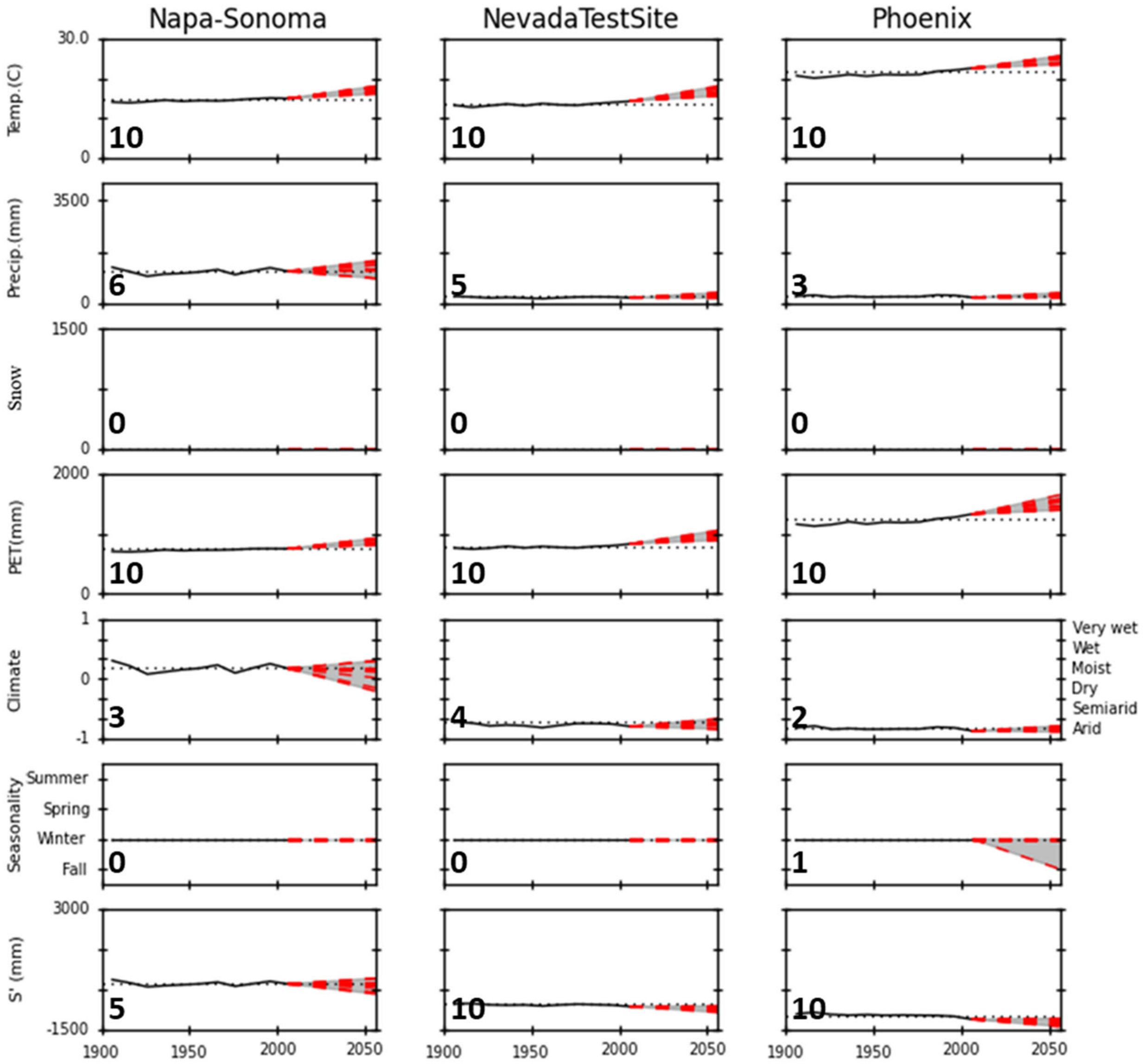

Seattle
SiskiyouNF
Spokane
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
4
2
6
Snow
1500
0
0
0
10
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
5
2
3
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
2
0
1
S' (mm)
3000
-1500
1
0
7
1900
1950
2000
2050

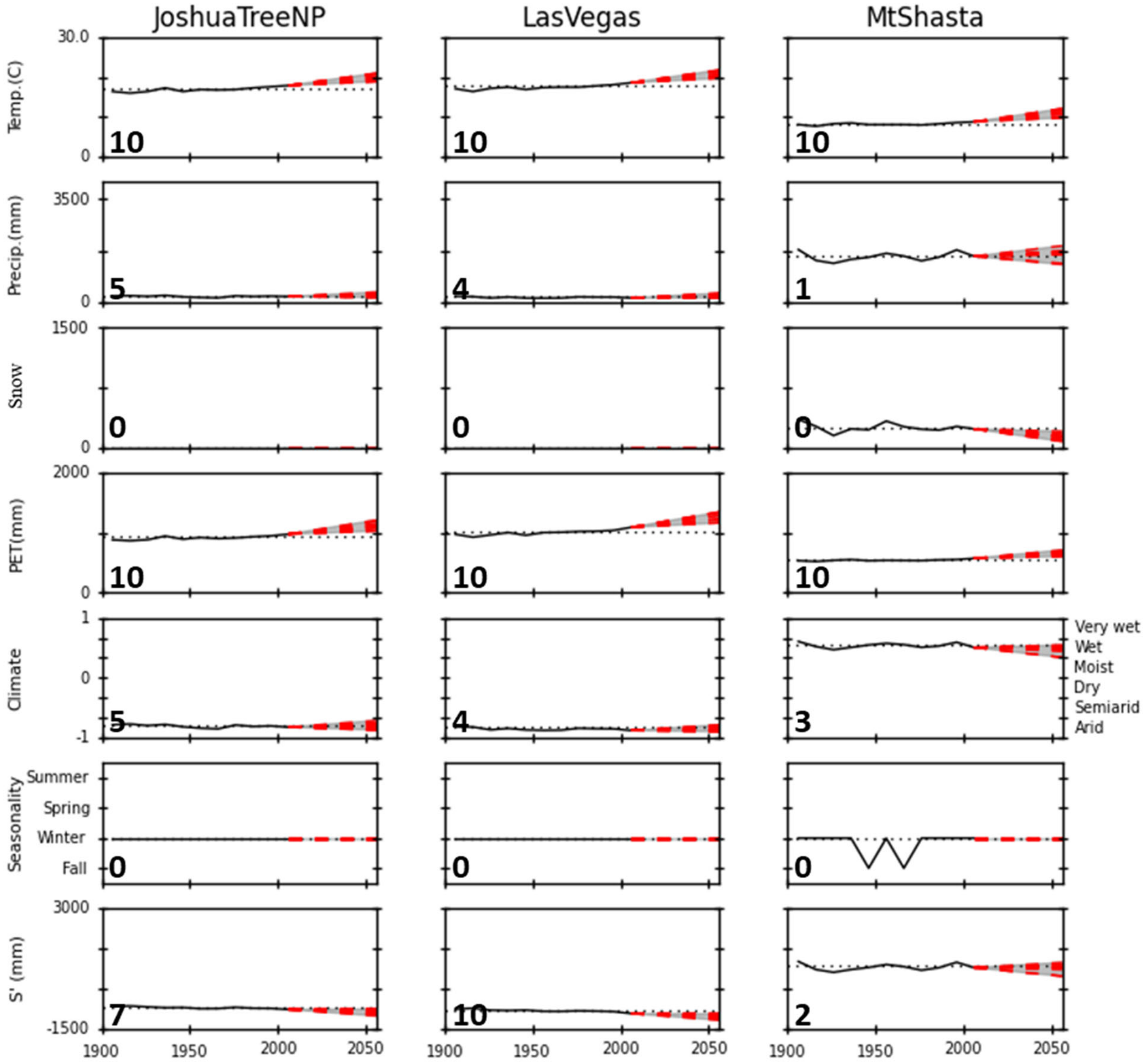

UmatillaNF
Willamette
Yakima
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
6
3
3
Snow
1500
0
6
0
0
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
3
4
0
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
4
0
0
S' (mm)
3000
-1500
3
2
6
1900
1950
2000
2050

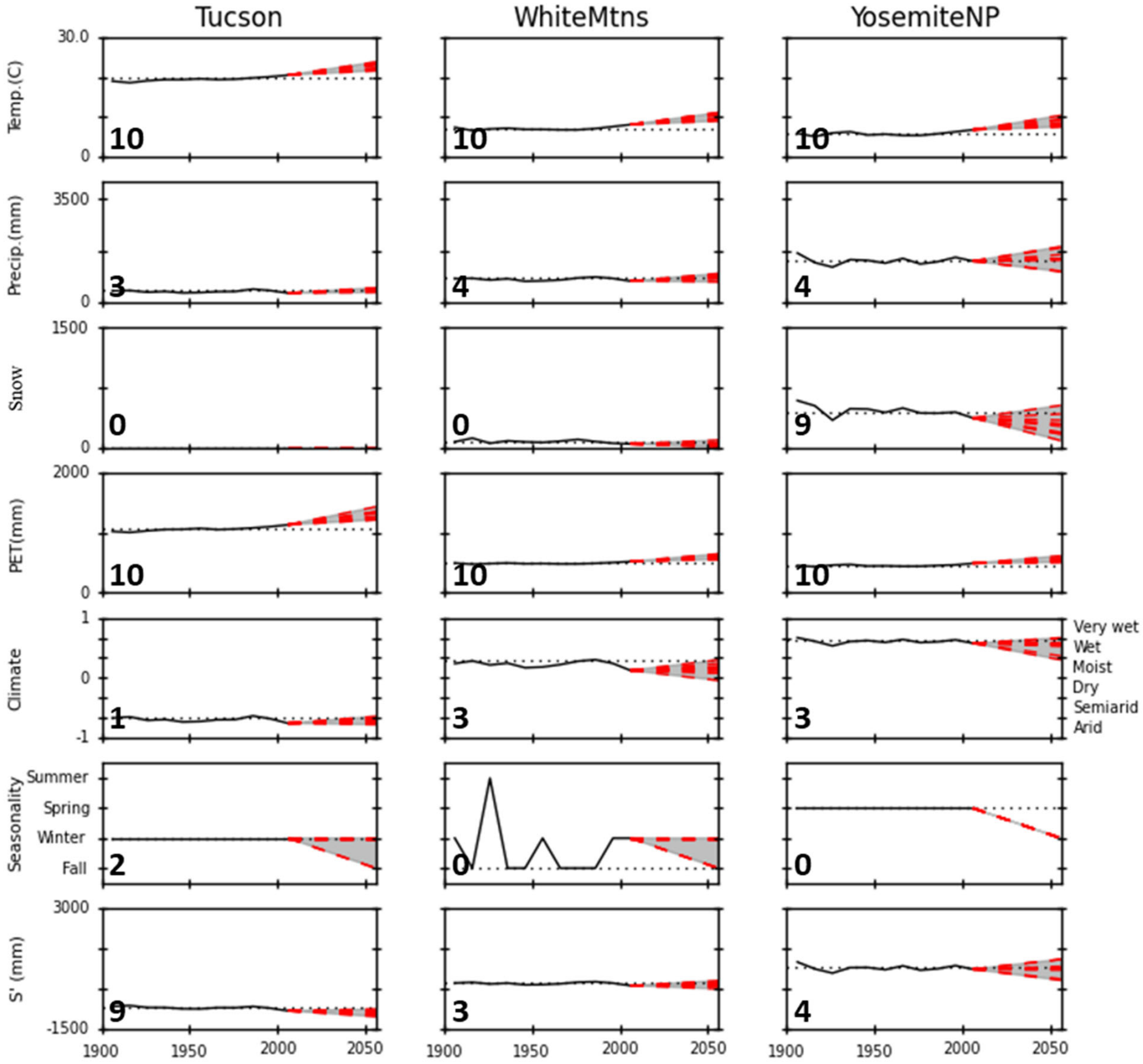

Arcata-HumboldtCo
Bakersfield
BattleMtn
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
3
4
6
Snow
1500
0
0
0
0
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
3
4
4
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
0
0
S' (mm)
3000
-1500
2
9
7
1900
1950
2000
2050


DeathValleyNP
Flagstaff
Fresno
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
5
3
5
Snow
1500
0
0
0
0
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
5
4
4
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
0
0
S' (mm)
3000
-1500
10
4
8
1900
1950
2000
2050

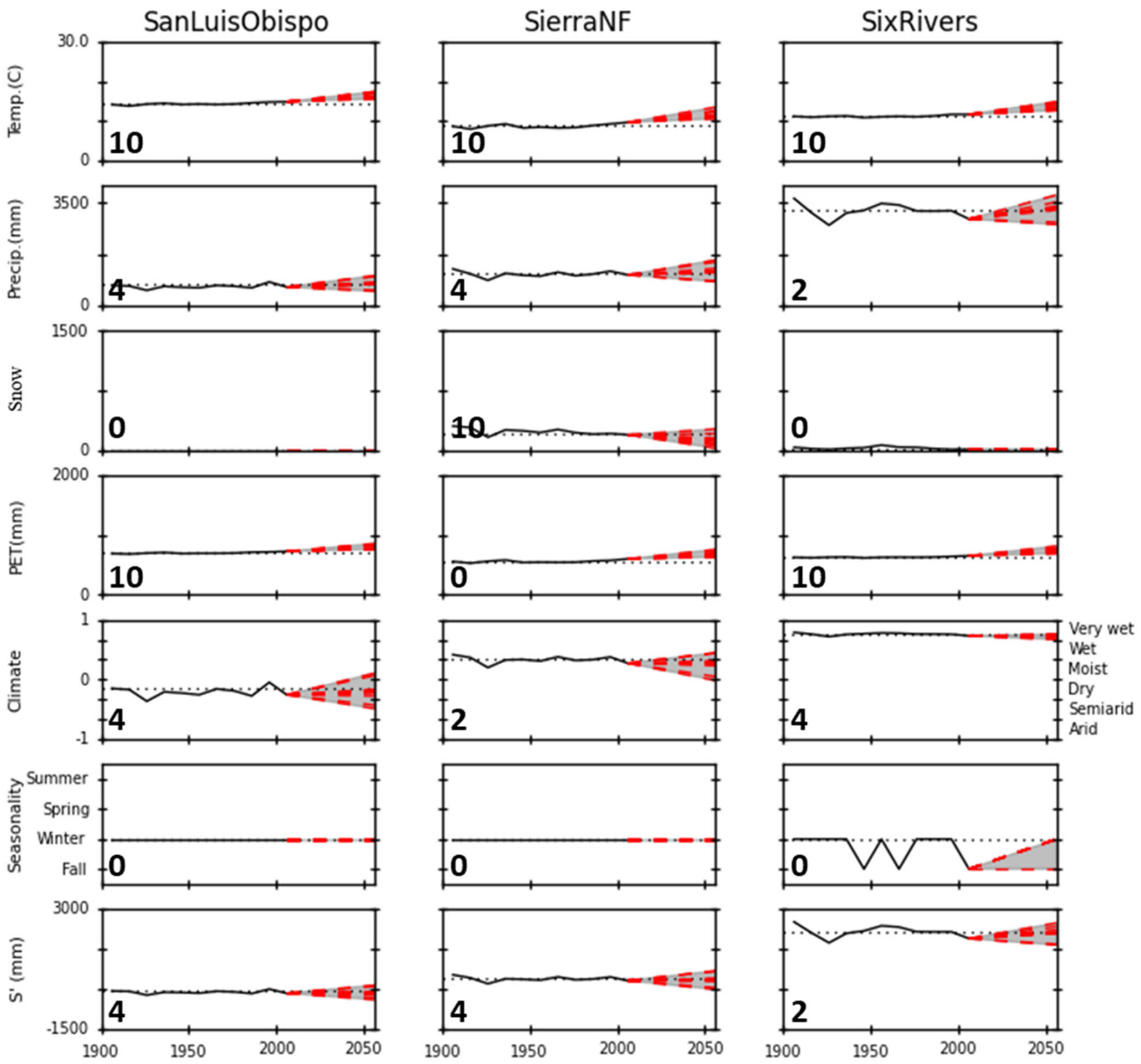

GrandCanyonNP
GreatBasinNP
HighSierras
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
4
4
2
Snow
1500
0
0
0
1
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
6
4
2
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
1
0
S' (mm)
3000
-1500
10
5
4
1900
1950
2000
2050

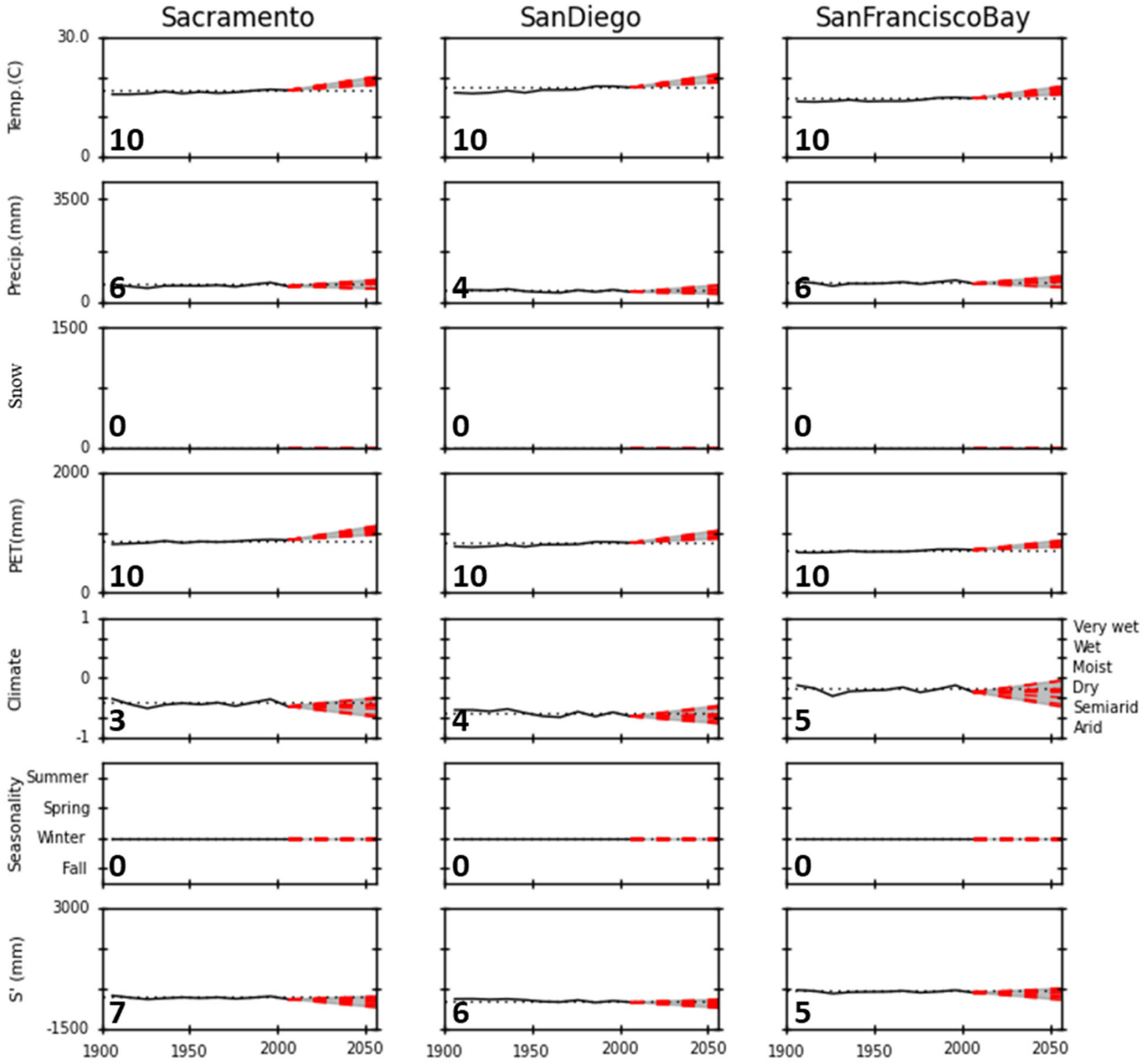

Napa-Sonoma
NevadaTestSite
Phoenix
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
6
5
3
Snow
1500
0
0
0
0
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
3
4
2
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
0
1
S' (mm)
3000
-1500
5
10
10
1900
1950
2000
2050


JoshuaTreeNP
LasVegas
MtShasta
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
5
4
1
Snow
1500
0
0
0
0
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
5
4
3
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
0
0
S' (mm)
3000
-1500
7
10
2
1900
1950
2000
2050

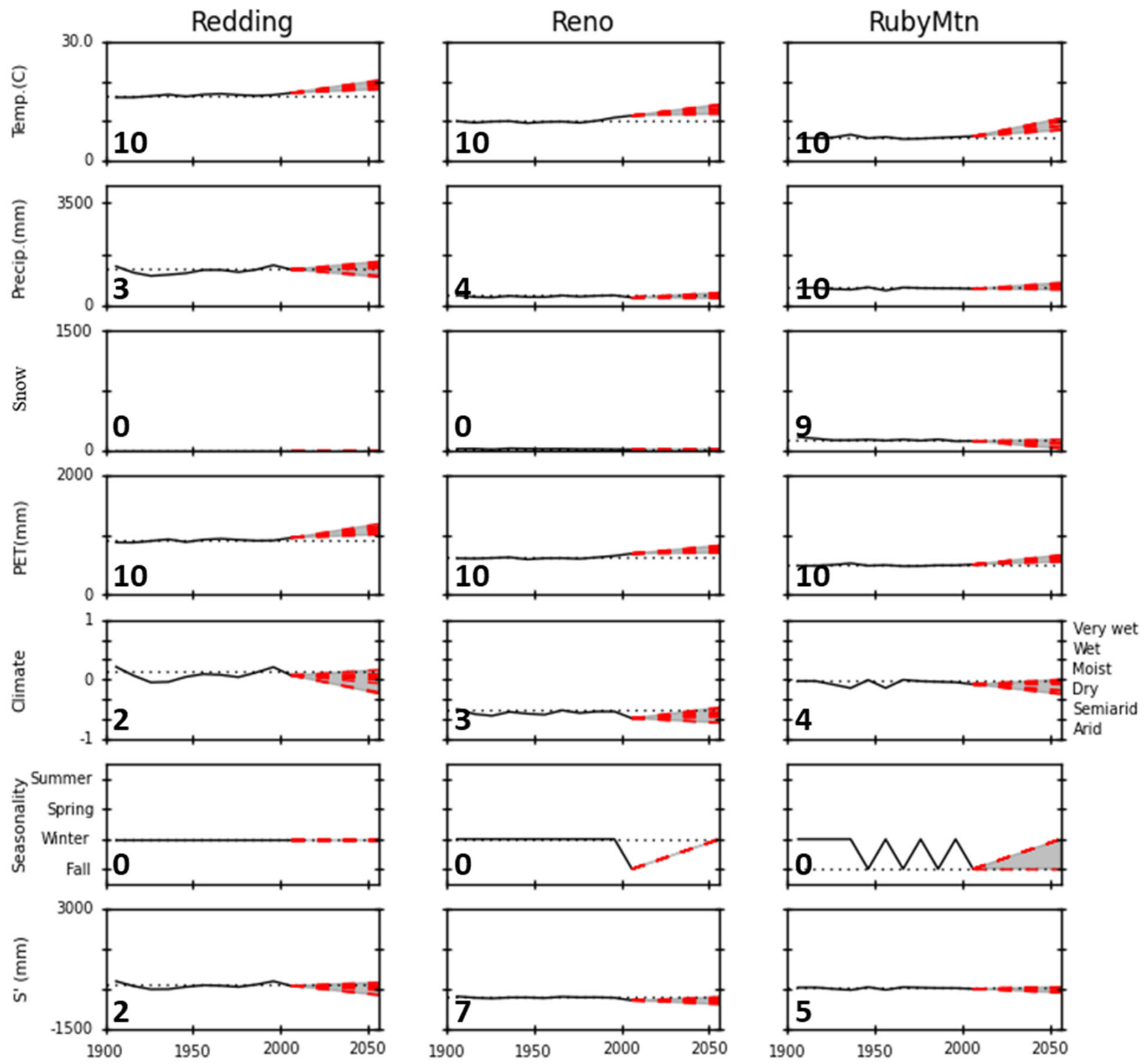

Tucson
WhiteMtns
YosemiteNP
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
3
4
4
Snow
1500
0
0
0
9
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
1
3
3
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
2
0
0
S' (mm)
3000
-1500
9
3
4
1900
1950
2000
2050

1082


SanLuisObispo
SierraNF
SixRivers
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
4
4
2
Snow
1500
0
0
10
0
PET(mm)
2000
0
10
0
10
Climate
1
0
-1
4
2
4
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
0
0
S' (mm)
3000
-1500
4
4
2
1900
1950
2000
2050



Sacramento
SanDiego
SanFranciscoBay
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
6
4
6
Snow
1500
0
0
0
0
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
3
4
5
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
0
0
S' (mm)
3000
-1500
7
6
5
1900
1950
2000
2050


Redding
Reno
RubyMtn
Temp.(C)
30.0
0
10
10
10
Precip.(mm)
3500
0
3
4
10
Snow
1500
0
0
0
9
PET(mm)
2000
0
10
10
10
Climate
1
0
-1
2
3
4
Very wet
Wet
Moist
Dry
Semiarid
Arid
Seasonality
Summer
Spring
Winter
Fall
0
0
0
S' (mm)
3000
-1500
2
7
5
1900
1950
2000
2050