Integrated Scenarios of Climate, Hydrology, and Vegetation for the Northwest

FINAL REPORT

June 30, 2014

1. ADMINISTRATIVE

Project title: Integrated Scenarios of Climate, Hydrology, and Vegetation for the Northwest

Agreement #: #G12AC20495

Award recipients:

Oregon State University (OSU): Philip Mote, David Turner
University of Washington (UW): Dennis P. Lettenmaier
Conservation Biology International (CBI): Dominique Bachelet
University of Idaho (UI): John Abatzoglou

Time period covered by report: 9/17/2012 through 6/30/2014

Actual total cost: $374,645

2. PUBLIC SUMMARY

The public summary should be concise and informative, and should be self-contained and intelligible to a layperson. In less than 300 words please describe your major scientific achievements to a non-scientific community (i.e., in non-scientific language) including major benefits of your research to society at large. Highlight the findings and significance of your research to expanding general knowledge in your scientific discipline, and the application of the results of your research to address significant societal problems. The NW CSC may use the public summary in publicly-distributed documents and other materials.

Climate change is expected to look different in different parts of the world. For this reason, regionally specific projections are critical to help farmers, foresters, fish and wildlife managers, city planners, public utility providers, and others plan how best to adapt.

In the Northwest, temperatures will likely increase 2-15 degrees Fahrenheit by 2100. The region's winters may become slightly wetter and its summers may be drier; unlike the temperature changes, however, these may not be clearly different from conditions observed in the past century. Snowpack will likely decrease substantially, and snowmelt runoff may occur earlier in the year, leading to increased winter runoff, earlier and decreased spring runoff, and decreased summer soil moisture content and runoff.

Forest types are expected to shift towards mixed evergreen-deciduous types, better adapted to warmer drier conditions. For example, coastal maritime evergreen forests adapted to cool conditions because of the proximity of the ocean are projected to shift to subtropical mixed-forests when disturbances allow their replacement. Wildfires will most likely become more frequent and severe over the next several decades since western forests have abundant fuels currently too moist to ignite but becoming more flammable when longer drier summers become the norm. Forest productivity (e.g. wood production) will likely increase at higher elevations currently limited by cooler temperatures and short growing season, but will be limited across the region by greater evaporative demand and late summer soil drying. The distribution of Douglas-fir will shift upward in elevation as drought stress increases at low elevation sites. Climate can drive changes in forest types through changing productivity, competition for water, and disturbance (like fires). Many of these changes are already occurring (http://occri.net/reports).

Climate scientists from around the world collaborate regularly to produce global climate model simulations, the most recent of these being the World Climate Research Programme's latest Coupled Model Intercomparison Project (CMIP5). CMIP5 represents a collaborative effort of more than 20 climate modeling groups from around the world, using the same experimental setup, to provide the best available climate modeling. While CMIP5 makes possible many targeted studies of climate change, it does not provide the degree of resolution necessary to generate meaningful projections about likely climate changes for a given region. For example, CMIP5 does not distinguish the Cascade Mountains from the Willamette Valley, two parts of the Northwest that will likely see different climate impacts in future decades. Scientists must translate, or "downscale", climate data from CMIP5 to create impact models for things like forest and range dynamics, crop growth, and seasonal patterns of water availability.

The goal of the *Integrated Scenarios of the Future Northwest Environment* project was to use the latest global climate models from CMIP5, and state of the science models of vegetation and hydrology, to describe as accurately as possible what the latest science says about the Northwest's future climate, vegetation, and hydrology. Researchers in the project started by first evaluating the ability of CMIP5 models to simulate observed climate patterns in the Northwest region. The researchers then used the best performing models to project likely future changes to Northwest's climate, hydrology, and vegetation.

One product of this work is a series of freely available datasets that can be used to address specific management questions. These datasets are compatible with other hydrological and ecological modeling efforts and represent a next-generation climate change framework for land managers. This framework supports a range of management activities to increase the resilience of Northwest ecosystems, agricultural systems, and built environments. It allows the development of tools to help land managers identify the most vulnerable areas in the region and to develop strategies for reducing the impacts of climate change.

On April 17, 2014, results from the Integrated Scenarios of the Future Northwest Project were presented at a daylong workshop in Portland, Oregon. David Patte and Stephen Zystra of the U.S. Fish and Wildlife Service have made video from the workshop available.

The video can be accessed here:

Overview by Phil Mote: https://www.youtube.com/watch?v=3Nm17DjTdZ0&feature=youtu.be

Climate and downscaling
David Rupp
https://www.youtube.com/watch?v=KnG4_Cc_VL8&feature=youtu.be
John Abatzoglou
https://www.youtube.com/watch?v=8v-W-Qgg6AU&feature=youtu.be

Hydrology
Dennis Lettenmaier
https://www.youtube.com/watch?v=S6ffOmyZ8bU&feature=youtu.be
Bart Nijssen
https://www.youtube.com/watch?v=Q91yx_o8CvI&feature=youtu.be

Vegetation
Dominique Bachelet, Tim Sheehan and Ken Ferschweiler
https://www.youtube.com/watch?v=SHcxLmFePLs&feature=youtu.be

Datasets are available here:

Climate Downscaling: http://maca.northwestknowledge.net/
Vegetation: http://consbio.webfactional.com/integratedscenarios/
Hydrology: http://www.hydro.washington.edu and http://www.hydro.washington.edu/Lettenmaier/Models/VIC/

The *Integrated Scenarios of the Future Northwest Environment* Project was funded jointly by the Department of the Interior's Northwest Climate Science Center (us) and by the National Atmospheric and Oceanic Administration's Climate Impacts Research Consortium (http://pnwcirc.org). To learn more about the project visit: http://pnwcirc.org/a-look-at-our-integrated-scenarios-project-with-video/ or contact Phil Mote at pmote@coas.oregonstate.edu.

3. TECHNICAL SUMMARY

The technical summary should outline the goals of the original research project and provide a technical description of how these goals were or were not met, highlighting specific achievements. Please state major research accomplishments made possible by receiving NW CSC funding. Please indicate how your research results contributed to the advancement of scientific knowledge regionally and/or nationally.

The goal of the project was to generate coordinated scenarios of climate, hydrology, and land cover in consultation with a range of researchers including awardees of the NW CSC projects, using best-in-class global and regional climate models, surface and groundwater hydrology models, and vegetation (both potential vegetation and productivity) models, as well as state-of-the-science methods for downscaling.

Global and regional climate model (GCM and RCM, respectively) output were evaluated and GCM output was downscaled for direct use as inputs to hydrologic and land cover (vegetation) models, as described below. Data management and delivery were tailored to specific end uses in consultation with other funded CSC activities.

The project began with a meeting involving many cooperators and partners, including scientists funded by the NW CSC and selected partners from the cross-CSC climate scenarios working group. The objectives of the meeting were to: 1. Define the most important climate parameters to obtain, downscale, and distribute. These should be useful for diagnosing important climate properties and for running impacts models. 2. Define the most important criteria for evaluating GCM and RCM performance over a region; and identify an initial set of “best” climate scenarios. 3. Acquaint all participants with the state of science of the respective fields of modeling, data development, and data management. 4. Outline a detailed plan for carrying out the work described here.

3.1. Climate

GCM outputs from several hundred simulations from the Coupled Model Intercomparison Project (CMIP5) were acquired for a historical period and for the future using two scenarios of greenhouse gas concentrations, known as Representative Concentration Pathways (RCPs). All available simulations that had requisite data were statistically downscaled using the Multivariate Adaptive Constructed Analogues (MACA, Abatzoglou and Brown 2012) method, 1950-2005 for historical runs and 2006-2100 for RCP 4.5 and RCP8.5 for the entire contiguous USA. Twenty GCMs were downscaled, for a total of 40 future climate scenarios.

To meet the data needs of both the vegetation and hydrological modeling, two statistically downscaled datasets were generated using 2 distinct observational datasets as "training" data for MACA. The datasets further differ by spatial and temporal resolution, available variables, and their spatial domain.

CMIP5 GCM simulations were compared to observed 20th century climate of the Pacific Northwest and surrounding area. The GCMs were then ranked by their performance with respect to a selected suite of metrics. From the 20 GCMs that were downscaled using MACA, a core set of 10 GCMs was identified as better performing from the larger pool of models.

In addition to statistically downscaling CMIP5 GCM output, we dynamically downscaled a single GCM across the western US. The dynamical downscaling was done at coarser horizontal resolution than the statistical downscaling (25 km vs. 6 km), and for the future limited to the years 2030-2049, therefore the output could not be used directly to drive the vegetation and hydrological models. However, we generated very large ensembles of simulations per year by changing the initial conditions of each run. This gave us more power to identify robust, topographically influenced patterns in climate change in both space and time than that originating from GCMs.

3.2. Vegetation

The response of vegetation to climate change was simulated using two process-based models: MC2 and 3-PG. The dynamic vegetation model MC2 was used to simulate shifts in vegetation cover, dynamics of carbon stocks and fluxes, change in fire occurrence and effects, and change in hydrological fluxes driven by the changes in vegetation cover and disturbance regime. The 3-PG (Physiological Principles Predicting Growth) model was used to evaluate potential changes in tree species productivity.

The MC2 model was forced with climate futures projected by the 20 GCMs and 2 future greenhouse gas scenarios (RCP4.5 and RCP8.5) downscaled with MACA for the western U.S. (west of longitude 103W). For each of these futures, MC2 was run with and without its fire suppression algorithm. Because there was a large temperature difference between current conditions (based on PRISM climate) and projected early 21st century conditions, the fire model simulated extensive fires due to the drying of fuels in areas where fuels were not limiting. The projected fire effects are likely to be overestimated as an artefact of the lack of smooth transition between observed and projected climate. The use of a CO_2 fertilization effect (increased water use efficiency wth higher levels of atmospheric CO_2) allowed woody lifeforms to not only survive under drier conditins but also to expand into drier areas traditionally dominated by herbaceous lifeforms. This effect is moderate in MC2 but continues to be the subject of scientific enquiry as data are scarce to document the response of many species, especially mature trees, to increases in atmospheric CO_2 concentrations.

The 3-PG model was forced with 3 GCMs and 1 future greenhouse gas scenario (RCP8.5) downscaled with MACA for the western U.S. (west of longitude 103°W). We compared results with an earlier study (Latta et al. 2010) over Oregon and Washington that used a statistical approach based on climate data and forest inventory plot data. The two approaches agreed on a general trend of productivity increases at higher elevations and decreases at relatively low elevations. This conclusion assumes that water will be more abundant at high elevation but others have shown that this may not be the case. In some parts of the Cascades, bedrock geology may reduce deep water recharge (Tague et al. 2008) and high elevation evaporative demand (Daly et al 2009) may increase while water availability will continue to allow lower elevation (foothills) forests to withstand warmer conditions. The statistical approach simulated areas of productivity increase on the Oregon Coast Range but the 3-PG modeling approach simulated decreases. Such discrepancies in the spatial patterns of predicted changes in forest productivity highlight areas where model assumptions diverge and physiological responses of specific species can differ, especially when their adaptive capacity is not taken into account. Areas of discrepancy may also correspond to areas where the drivers of some modeling approaches are unreliable. Soil characteristics, generally unused in statistical approaches and standard species distribution models, are such drivers. It is also important to note that uncertainties in the climate drivers along coastlines are large and that the role of coastal influences such as fog, relative humidity due the proximity of the ocean, are not well represented.

3.3. Hydrology

Our research updated and extended prior efforts to understand the impacts of climate variability and climate change upon hydrology in the PNW. Advances include the incorporation of CMIP5 climate projections (RCP4.5 and RCP8.5), MACA-downscaled meteorological forcings, expansion to the western U.S. domain, and two land-surface/hydrology models.

We performed hydrologic simulations for the western U.S. (west of longitude 103W) for the period 1950-2099 using high-resolution (1/16th degree) implementations of the Variable Infiltration Capacity (VIC) model and the Unified Land Model (ULM) forced with downscaled climate model output. Twenty climate scenarios were used as input, from 10 GCMs with both RCP4.5 and RCP8.5. Hydrologic fluxes and state variables were archived at a daily timestep. Based on these simulations, we evaluated projected changes in the land surface water and energy balances, with particular focus on seasonal snowpack and streamflow. From our investigation, we conclude that an increasingly warm future climate will result in decreasing snowpack; generally increased winter runoff; earlier and decreased spring runoff; and decreased warm season soil moisture content and runoff.

The simulation data and basic summaries provided by this project provide a rich dataset and new starting point for investigations of hydro-climatic sensitivity, model uncertainty, climate change emergence, and water resource vulnerabilities to climate change and variability.

3.4 Achievements of this project

As expected, this project provided regional and national leadership in coordinating climate-related science. Numerous scientists have downloaded and begun using the MACA data, and interest in the April 17 workshop was quite high, with approximately 75 attending in person and another 150 viewing the simultaneous C3 (Climate Change Collaborative, C3.gov) webinar. Morever, three other CSCs have expressed strong interest in applying both MACA and our climate model evaluation approach; the SE CSC even funded us to do so. By offering an intellectual framework to provide consistency among the various modeling efforts, we have paved the way for future climate science in the western US.

4. PURPOSE AND OBJECTIVES

This section should include information about the issue(s) the project addressed, and the community it serves. What were the original objectives identified during project initiation? Were they met? Have changes eliminated, added to, or modified the original objectives? Please describe any differences from the original proposal and why these changes were made. This is valuable information for others who are studying the same topic and essential for our evaluation of the project.

A wide range of planning activities, scientific research, and decision support tools now require some representation of future climate, hydrology, and/or vegetation. While vigorous research is underway separately in these areas, several obstacles prevent the optimal delivery of future scenarios. First, one can download over 200 global and regional climate model simulations, but the user has little guidance on selecting and interpreting these simulations. Second, previous vegetation and hydrologic modeling has been carried out independently, with independent selections of climate models as inputs, so the studies are rarely cross-comparable. Third, new efforts at regional climate modeling bring better spatial resolution and physically based descriptions of future climate, but have not yet been widely incorporated. Fourth, careful descriptions of the statistics of uncertainty and the sources of uncertainty are generally lacking.

This effort, focusing on the Northwest but widely applicable, aimed at overcoming at least the first two of these obstacles while making progress on the others. Building on federal investments, and on the expertise in the NOAA-funded Climate Impacts Research Consortium, we pointed out an opportunity for NW CSC to co-lead a new and more coordinated and thoughtful approach to envisioning the Northwest's future environment. As described in detail below, we:

- engaged scientists, especially those funded by the CSC, and decision-makers to shape the Project,

- evaluated global and regional climate models, selected a 'core set' of 10 global models, and considered how to do the same with regional models,

- downscaled 20 of the global models for the contiguous USA using a new statistical approach developed by co-PI Abatzoglou,

- selected and calibrated an additional hydrologic model to join the oft-used Variable Infiltration Capacity (VIC) model, and performed simulations with both hydrology models using 2 socioeconomic scenarios for each of the core set of 10 GCMs (2 x 10 = "the 20 core scenarios"),

- performed simulations with the MC2 dynamic vegetation model for the western USA to estimate vegetation distribution, carbon stores and fluxes, and fire occurrence, area burned, and impacts, from 20 GCMs and 2 future scenarios,

- performed simulations with the 3-PG physiological forest growth model for the western USA to simulate net primary production, wood mass, and leaf area index during forest succession, as well as Douglas-fir presence/absence, for 3 representative climate scenarios,

- laid the groundwork for careful quantification of uncertainty and utilization of regional models.

The resulting datasets will be integrated and compatible with other hydrological and ecological modeling projects that ultimately will lead to a next generation climate change framework that allows land managers to identify potentially vulnerable areas; prioritize investment in projects to increase the resilience of forests and grasslands; and incorporate projected changes in fire danger into development of water and forest management plans, State forest assessments, and other strategic land management plans consistent with the DOI mission.

Changes to original objectives

Because of the interest expressed (including that from other CSCs), in downscaled climate data beyond the originally proposed domain of the Northwest US, we expanded the domain for downscaling to the entire conterminous United States (CONUS) including the Canadian portion of the Columbia basin. Moreover, the domains of the hydrologic modeling and vegetation were expanded to include the entire western US, and in the case of the hydrological modeling, also the Canadian portion of the Columbia basin.

In addition to increasing the spatial domains, we also used a set of 40 scenarios (20 GCMs x 2 RCPs) from the global climate model database, in place of the originally proposed 20 scenarios (10 climate models x 2 RCPs), for statistical downscaling of climate data and for driving the vegetation model MC2. However, we still identified a "core" set of 10 global models as recommended models, and used these for the hydrological modeling, as originally proposed. For the physiological forest growth model 3-PG, we used climate data derived from 3 global models, chosen to represent 3-end members of the plausible climate future.

Our collaborator on the 3-PG modeling (N. Coops, unfunded) planned to do species presence/absence simulations for multiple tree species but was able to complete the analysis only for

Douglas-fir because of limited human resources. CIRC will continue to work with Coops on the 3-PG analyses. Towards meeting our objective with respect to mapping climate change impacts on the geographic distribution of tree species, we have included a dataset from Rehfeldt et al. (2014) in the Integrated Scenarios Group folder on Data Basin. That study used CMIP5 climate scenarios and projected distributions of Douglas-fir and Ponderosa pine. It is in some ways an advance over the 3-PG approach that uses fixed parameters for each species because it accounts for differences among genetically different varieties of the two species. Neither approach however takes into account the role of disturbance (fire) in projecting species resilience.

Lastly, we originally proposed to statistically downscale climate simulations from the North American Regional Climate Change Assessment Program (NARCCAP). The NARCCAP simulations themselves are dynamically-downscaled global climate simulations using embedded regional climate models of North America. However, with their horizontal resolution of 50 km, we found that the NARCCAP data are too coarse and biased to meet our hydrological and vegetation modeling requirements directly, therefore additional statistical downscaling is necessary. We further proposed to use statistically downscaled NARCCAP data as inputs to a hydrological model, but upon investigation we found that the additional climate signal introduced by NARCCAP was too weak to justify the very considerable effort required and chose not to pursue that. However, this omission was more than offset, in terms of added value to the larger climate impacts assessment community, by expanding the domains of the CMIP5 downscaling and the hydrology and vegetation modeling.

5. ORGANIZATION AND APPROACH

This section of the report explains in task oriented terms how the research activities of the project were conducted. Briefly list which research methods were used to achieve results and why they were chosen by the team.

5.1. Climate

5.1.1. Evaluation of global climate model regional performance

Performance, or credibility, of global climate models (GCMs) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) was assessed based on the GCMs' abilities to reproduce the observed 20th-century climate of the Pacific Northwest United States (PNW) and surrounding region. From monthly temperature and precipitation data from 41 CMIP5 GCMs, we calculated a suite of statistics, or metrics, that characterize various aspects of the regional climate. GCMs were ranked in their credibility using two methods. The first simply treated all metrics equally. The second method considered two properties of the metrics: 1) redundancy of information (dependence) among metrics, and 2) confidence in the reliability of an individual metric for accurately ranking models. Confidence was related to the uncertainty of the estimate of the metric (e.g., the standard error of the estimate) relative to inter-model variability. Performance metrics from the CMIP5 GCMs were compared to the previous generation of CMIP3 GCMs. Methods are described fully in Rupp et al. (2013).

5.1.2. Statistical downscaling of global climate simulations (MACA)

Global climate model (GCM) outputs from several hundred simulations from CMIP5 were acquired for a historical period and for two future scenarios known as Representative Concentration Pathways (RCPs). All available simulations that had requisite data were statistically downscaled using the Multivariate Adaptive Constructed Analogues (MACA, Abatzoglou and Brown 2012), 1950-2005 for historical runs and 2006-2100 for RCP 4.5 and 8.5.

We coordinated the resolution of the final downscaled datasetds based on the needs of both the ecological and hydrologic modeling teams to ensure compatibility of spatial and temporal scales. This required downscaling to both a 1/24th degree and 1/16th degree grid using 2 different training datasets and to provide data at both the monthly and daily scales. We additionally derived monthly dew point temperature from specific humidity, as the ecological modeling group needed this field.

While we only were obligated to downscale climate simulations for the core set of 10 GCMs, additional resources from CIRC (NOAA RISA) allowed us to apply our downscaling to a set of 20 GCMs for which all daily outputs were available from CMIP5 for both RCP4.5 and RCP8.5 experiments (Table 1). We augmented the original MACA to better address some of the biases inherent in GCM fields. The updates included (i) continuous trend preservation of the original GCM signal using a 31-year moving window over both historical and future periods, 2) use of a reduced set of analog patterns but including a residual error term from the constructed analogs, and 3) joint bias correction of temperature and precipitation to remove inter-model biases in temperature coincident with precipitation. These modifications resulted in significant improvements in downscaling as seen in a cross-validation study.

Building on a previous project supported by the NW CSC, we used MACA as our preferred approach for downscaling over other available statistical downscaling approaches such as bias correction-spatial downscaling (BCSD) for the following reasons:

- MACA is able to directly use daily output from GCMs and is thus more readily able to capture changes in higher-order climate statistics (e.g., extremes).

- The spatial downscaling from MACA uses observed spatial patterns rather than using interpolation approaches.

- MACA can be extended to multiple variables. We downscaled daily temperature, precipitation, wind speed, downward shortwave radiation and humidity.

- MACA downscales some of the variables in sets in order to preserve the dependencies between the variables. For example, the downscaling of temperature jointly with precipitation has been seen to produce better results in capturing historical statistics of snowfall and correct for model biases specific to precipitating days and thus precipitation phase. This bias correction is important for subsequent hydrologic modeling.

We applied MACA to daily outputs from 20 CMIP5 models for historical (1950-2005), RCP4.5 and RCP8.5 (2006-2100) modeling experiments utilizing the 1/16th degree surface meteorological data of Livneh et al. (2013). Due to the interest in downscaled outputs beyond our original domain, we expanded the spatial domain for the downscaling to the entire conterminous United States including the Canadian portion of the Columbia basin. We have also rescaled outputs from two GCMs that had 360-day years to conform to a 365-day year calendar. Given the disparate training datasets used by the vegetation and hydrologic modeling teams, we provided an earlier version of downscaled MACA fields aggregated to monthly timescales at a 4-km spatial resolution for the same 20 CMIP5 models based on the 1/24th degree surface meteorological dataset of Abatzoglou (2013) for use in MC2.

Table 1. Downscaled CMIP5 GCMs, ranked in order of performance. Core ten marked with *.

CCSM4*
CNRM-CM5 *
HadGEM2-ES*
HadGEM2-CC*
CanESM2*
IPSL-CM5A-MR*
bcc-csm1-1-m*
MIROC5*
NorESM1-M*
CSIRO-Mk3-6-0*
IPSL-CM5A-LR
BNU-ESM
MRI-CGCM3
inmcm4
bcc-csm1-1
GFDL-ESM2M
GFDL-ESM2G

MIROC-ESM-CHEM
MIROC-ESM
IPSL-CM5B-LR

5.1.3. Regional climate modeling for the PNW

While MACA statistical downscaling is an efficient tool for generating climate change scenarios at high resolution, it does not explicitly simulate the role that the region's varied topography may have on modulating the climate change signal. This is because the pattern of change in the statistically downscaled data is still driven by the coarse GCM which lacks topographic detail over the region. For this reason, we used the dynamical downscaling framework "regCPDN" that makes use of volunteers' personal computers to generate thousands of regional climate simulations for the future period 2030-2049 at 25km spatial resolution for the western US. These projections of the future climate build upon our previous simulations of the period 1960-2010 using observed sea surface temperatures (SSTs) as boundary conditions to the single GCM-RCM combination HadAM3p-HadRM3p. The period 2030-2049 used greenhouse gas concentrations and SSTs consistent with RCP4.5. The resulting "superensemble" of climate simulations offers an unprecedented combination of statistical and spatial resolution.

The RCM simulations were used primarily to examine spatial patterns of climate change, thus providing additional features of regional climate change that may not be present in the statistically downscaled GCM datasets.

5.2. Vegetation

5.2.1. Potential vegetation (MC2)

MC2 dynamic global vegetation model (DGVM), the C++ version of the MC1 DGVM (Bachelet et al. 2001), simulates potential vegetation -- i.e., the vegetation that would occur on the landscape given local climate and soil conditions, ignoring land use legacies from human occupation. Consequently, vegetation model simulation results for current conditions often disagree with observed vegetation. However, projected potential vegetation dynamics under future conditions provide valuable insights on how native vegetation may respond to climate change while projections of future land use are highly uncertain. Moreover, relying on predicted changes in a particular species range (contraction or expansion) alone can bring surprises when an extreme climate event or pest outbreak extirpates such species, or if invasive or "climate refugee" species take over. In addition to the potential vegetation distribution, MC2 simulates carbon cycle, fire occurrence and effects (Figure 1). MC2 was run with PRISM historical climate followed by climate futures projected by 20 CMIP5 GCMs downscaled using MACA over the western US, under RCP 4.5 and 8.5 for a total of 40 climate futures. For each of these futures, MC2 was run with and without its fire suppression algorithm.

Output data included 36 variables and for all runs comprise approximately 300 GB of data per run. The vegetation model was run on the NASA Earth Exchange (NEX) platform at the original 4km spatial resolution of the downscaled climate data since it required the large-scale computing power to produce results for the 40 climate futures in a reasonable time frame.

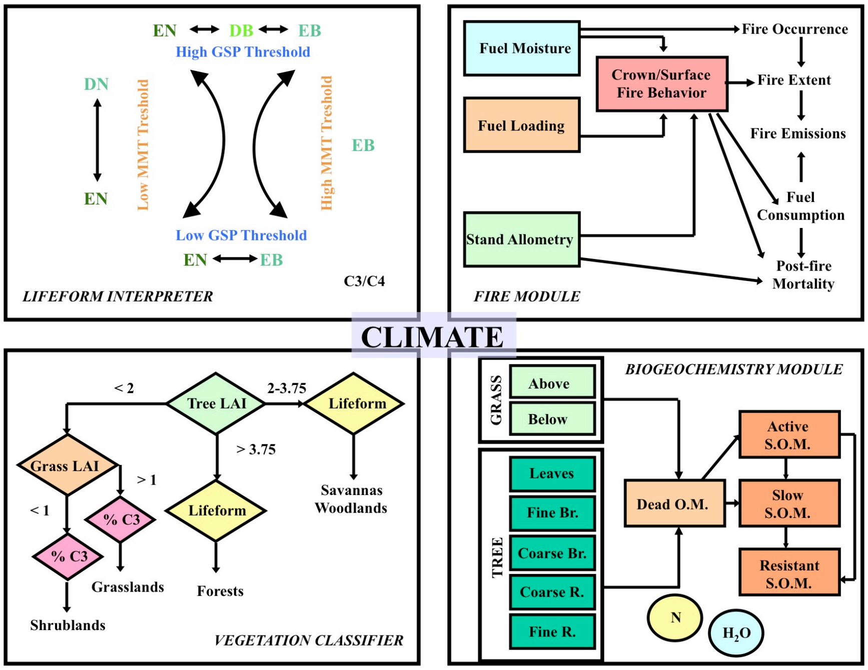

Figure 1. Diagram representing the four components of the MC2 vegetation model. The biogeochemistry model simulates carbon and nitrogen cycles as well as hydrological flows for each grid cell where the vegetation type is based on a combinations of woody and herbaceous lifeform competing for light, water and nutrients. Vegetetaion type is determined using a set of rules based on climate and biomass thresholds. The fire modules simulates fire occurrence using fuel load and fuel moisture thresholds and modifies carbon pools based on fire intensity and vegetation structure. (E=evergreen, D=deciduous, N=needleleaf, B=broadleaf, LAI=leaf area index, GSP=growing season precipitation, MMT=minimum monthly temperature, SOM=soil organic matter, N=nitrogen, R=roots, Br=branches)

In order to limit the number of maps and graphics to be generated while using an ecologically relevant reporting unit, we chose the EPA Level III ecoregions to summarize our results.

5.2.2. Forest potential productivity (3-PG)

Potential productivity is the productivity of ‘potential’ vegetation (see previous section). Each 3-PG model run (e.g. Coops et al. 2010) consisted of a 50-year simulation of forest succession using a decade of climate data that was recycled five times. The model produced spatial output on the potential leaf area index, wood mass, net primary production of a 50-year old conifer forest for each decade from the 1950s to the 2090s. The Douglas-fir presence/absence was based on a decision tree algorithm that included climate data and 3-PG outputs (e.g. Coops et al. 2011). Three of the CMIP5-MACA scenarios representing a range of future climates were evaluated (MIROC5 RCP8.5, HadGEM2-ES RCP8.5, GFDL-ESM2M RCP4.5).

5.3. Hydrology

We performed hydrologic simulations using the latest VIC model release (version 4.1.2) and the Unified Land Model (Livneh et al. 2011). For each model, MACA-downscaled GCM forcings for 10 GCMs were used to drive historical and future period simulations spanning 1950-2005 and 2006-2100, respectively. The downscaling trains the time series of each GCM to the 1950-2005 portion of the gridded historical observation dataset of L13 (Livneh 2013).

VIC is a semi-distributed hydrologic model that represents land-surface processes by incorporating variable vegetation, soil types, and topography through energy and water balance equations (Liang et al. 1994; Gao et al. 2012). The VIC model has been used in numerous studies of the hydrologic effects of climate variability and change on regional (e.g. in the Northwest, Payne et al. 2004; Elsner et al. 2010; Hamlet et al. 2013) and global scales (Nijssen et al. 2001). Outputs of VIC include snow water equivalents (SWE), soil moisture, runoff, streamflow, evapotranspiration, and potential evapotranspiration, which are useful in describing the habitat of many species ranging from Pacific Salmon (Mantua et al. 2010) to Douglas-fir trees (Littell et al. 2010).

The Unified Land Model (ULM) combines the Noah Land Surface Model and the Sacramento Soil Moisture Accounting Model (SAC). While ULM is newer than VIC, the underlying models (Noah and SAC) are well established. Noah is well-suited to running in land-atmosphere coupled weather and climate models. SAC is used extensively in hydrologic prediction by the National Weather Service. ULM uses the vegetation, snow, frozen soil, and evapotranspiration components of Noah and the soil moisture accounting capability of SAC (Livneh et al. 2011).

6. PROJECT RESULTS

Present your project results. Quantitative results (numerical and/or statistical data) and qualitative results (descriptions of how well or poorly something worked) are both important. Tables, graphs and other figures representing your data are excellent ways to summarize data and present them in an accessible way.

6.1. Climate

6.1.1. Evaluation of global climate model regional performance

The CMIP5 GCMs showed wide range in their abilities to reproduce the observed regional climate. Overall, the CMIP5 GCMs did not perform substantially better than the earlier CMIP3 GCMs. Detailed results of the evaluation were published in the *Journal of Geophysical Research: Atmospheres* (Rupp et al. 2013).

The relative errors for each performance metric used in the evaluation of the GCMs are shown in Fig. 2. Note that the performance of a GCM with respect to the others depended strongly on the performance metric. However, by using numerous metrics that span both spatial and temporal aspects of temperature and precipitation, we identified a core set of 10 GCMs that perform well overall (see Table 1). Because the core set was limited by the data requirements of MACA, some of the "best" models were not included in the core set (e.g., CESM1-CAM5).

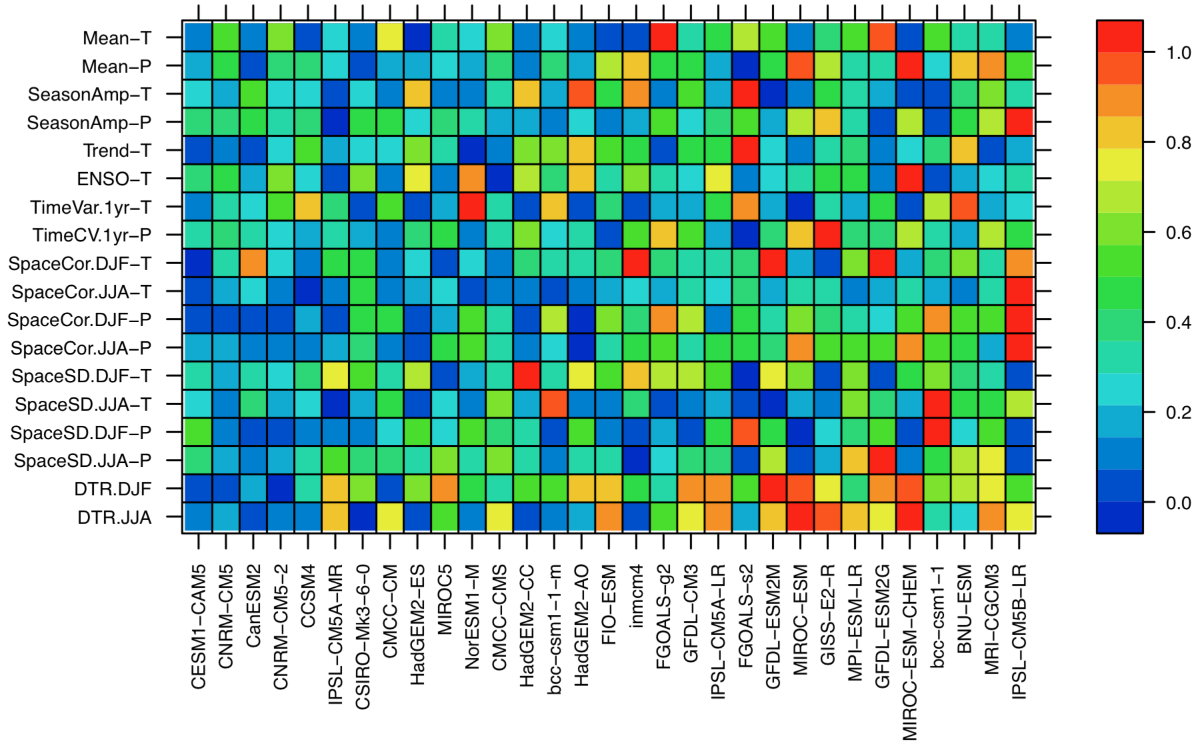

Figure 2. Relative error of the ensemble mean of each performance metric for each CMIP5 GCM for which simulations under experiments RC4.5 and RCP8.5 were also available. Models are ordered from least (left) to most (right) total relative error, where total relative error is the sum of relative errors from all metrics. Adapted from Rupp et al. (2013).

6.1.2. Statistical downscaling of global climate simulations (MACA)

The MACA downscaling of 20 GCM outputs and 2 future scenarios resulted in over 11 terabytes of downscaled climate data. Although there are numerous ways to analyze the data, we provide here a couple examples for looking at the future projections from this dataset (more like these can be explored in further detail through our webpage http://maca.northwestknowledge.net). Fig. 3 shows the projected changes in Dec-Feb precipitation for years 2040-2069 of experiment RCP 4.5 to late 20th century climatology across the 20 GCMs for both the downscaled and raw GCM data. Fig. 4 summarizes these changes by showing the multi-model mean response and the level of model agreement for both the downscaled and raw GCM data.

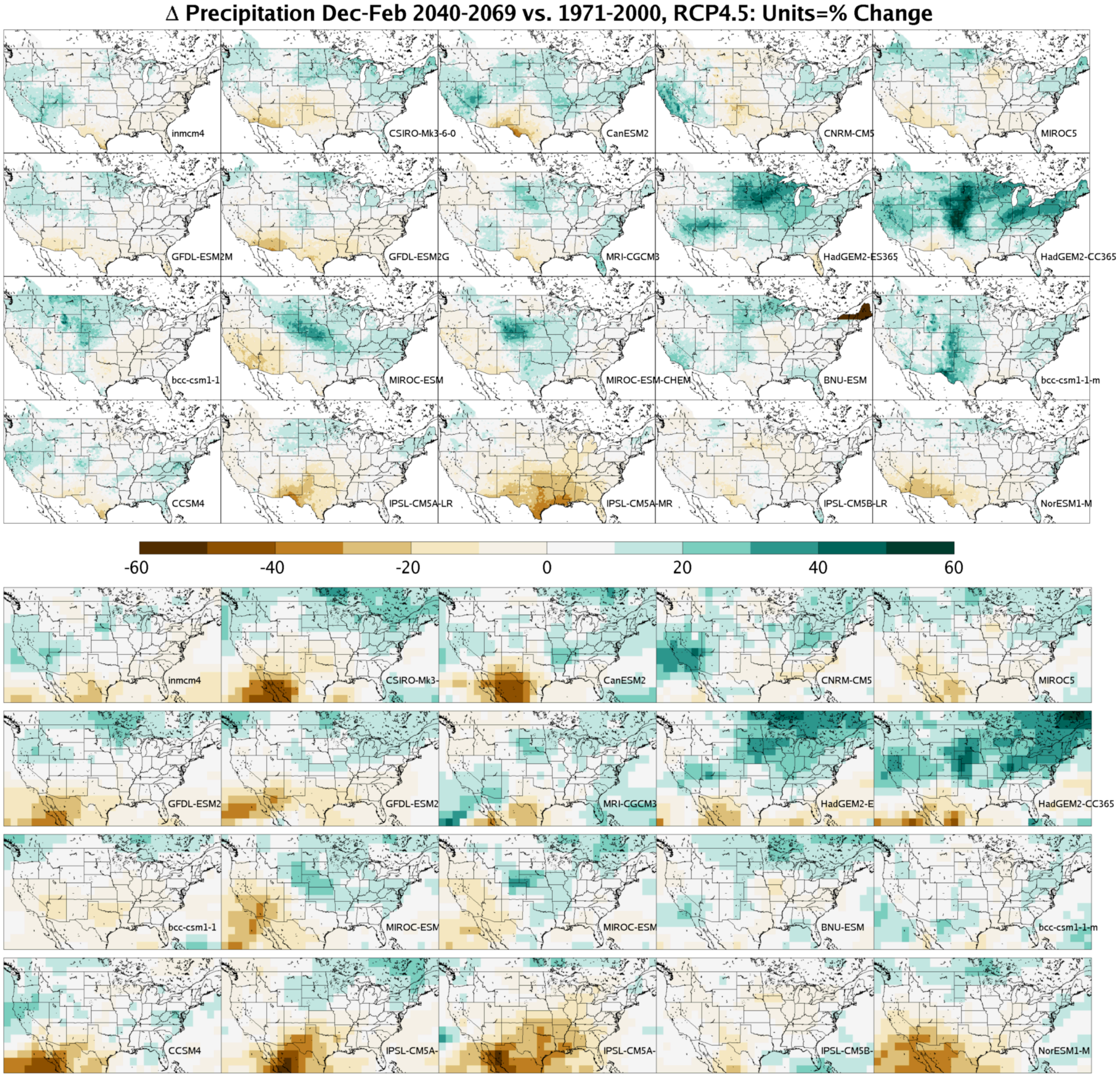

Figure 3. Projected changes in mean Dec-Feb precipitation from the years 1971-2000 to the years 2040-2069 of experiment RCP4.5 for the (top) downscaled and (bottom) raw 20 CMIP5 climate models.

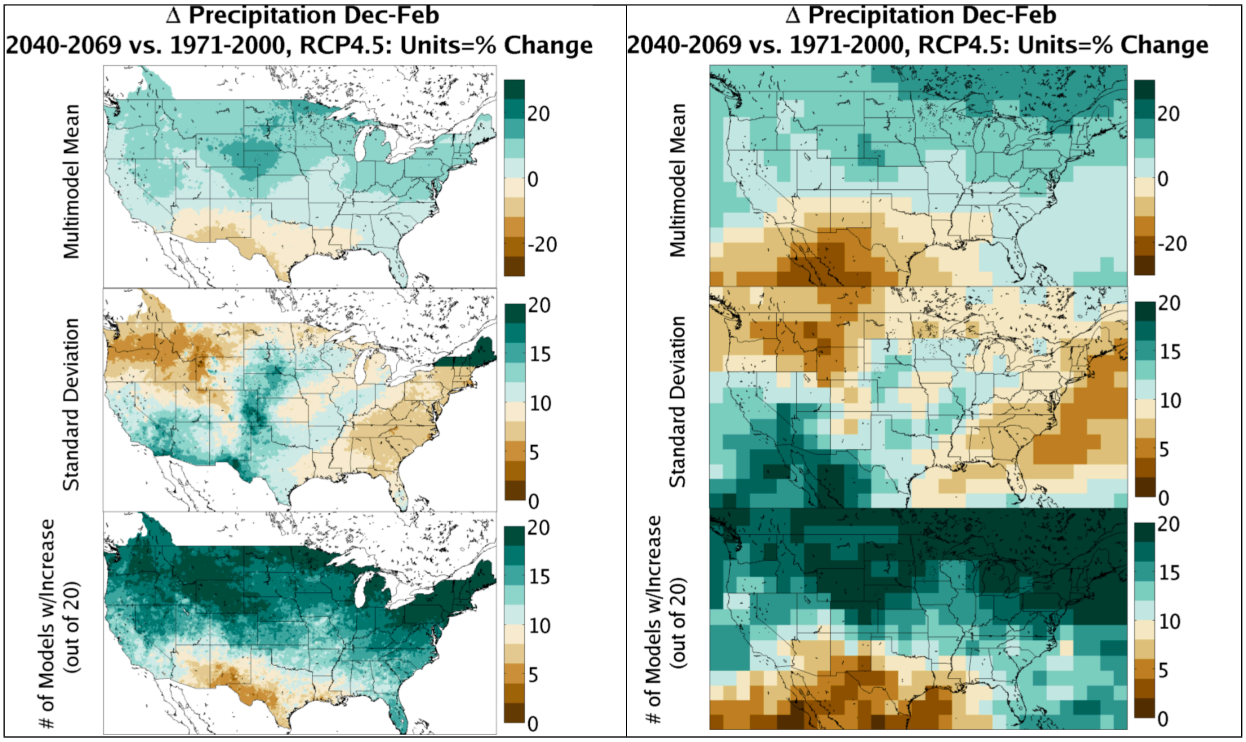

Figure 4. (top) Projected 20 model mean change and in Dec-Feb precipitation from the years 1971-2000 to the years 2040-2069 of experiment RCP4.5 for (left) downscaled and (right) raw CMIP5 climate models. The middle panels show the standard deviation of change while the bottom panels provide a measure of model agreement as they show the number of models (out of a total of 20) that project an increase.

The climate datasets have been converted to NetCDF format using Climate and Forecast (CF) metadata standards to ensure compatibility across platforms. All datasets have been transferred to the Northwest Knowledge Network (NKN) for public access. NKN offers a number of services for users to access the raw data including a THREDDS server for subsetting the data in space or time and for users to access/subset the data directly using OPeNDAP in their software of choice.

6.1.3. Regional climate modeling for the PNW

The regional climate modeling showed a rich spatial pattern of temperature change across the western US that is associated with major topographic features in the region (Fig. 5). For example, the change in mean spring temperature (from 1986-2005 to 2030-2049) varied from < 2°C to > 4°C, with greater warming occurring at higher elevations. Fig. 5 clearly highlights greater warming in the Cascades, Sierra Nevadas, and mountain ranges of Utah, than in the surrounding lower areas.

Greater warming in the spring was also clearly associated with greater decreases in the April snowpack, implying a strong positive feedback between snow loss and temperature change probably due to changes in albedo (Fig. 6).

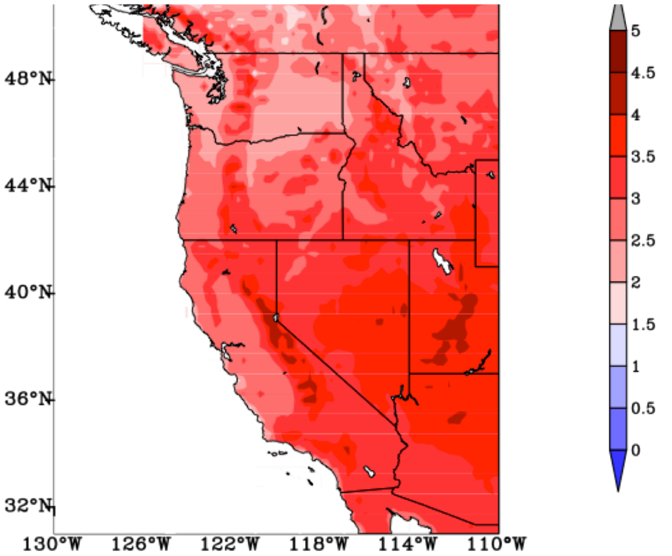

Figure 5. Map of mean spring temperature change (°C), 2030-2049 minus 1986-2005, from an ensemble of over 400 regional climate model simulations, showing greater warming at higher elevations (e.g. the Cascades, Sierra Nevadas, and mountain ranges in Utah).

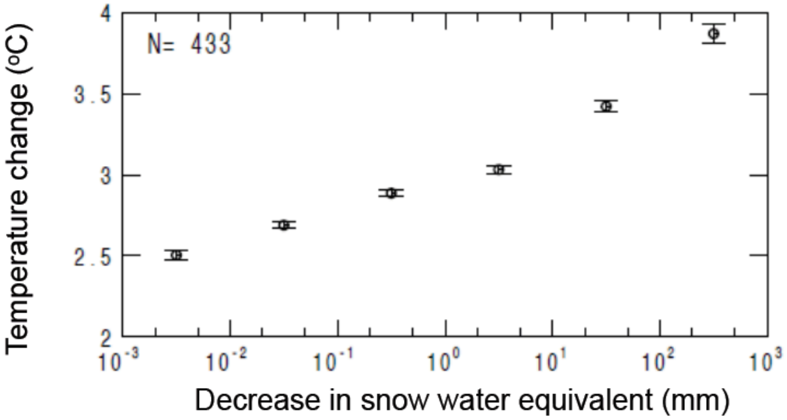

Figure 6. Mean spring temperature change, against the decrease in April snow water equivalent (SWE) (2030-2049 minus 1986-2005). Values from all grid points in the Pacific Northwest were binned by change in the mean April SWE. Error bars show +/- 1 standard deviation.

6.2. Vegetation

6.2.1. Potential vegetation (MC2)

Four primary results from the vegetation modeling utilizing MC2 are:

- Large shifts in potential vegetation towards warmer types (e.g. temperate to subtropical forest types, warm subtropical grasslands replacing cool temperate grasslands).

- An expansion of forest and woodland types enhanced by a moderate CO_2 effect on water use efficiency and production when water availability declines.

- An overall increase in carbon stocks because woody life forms extend their range. This increase is modulated by fire events that cause large carbon losses through fire emissions but also stimulates nutrient release and fast regrowth (Fig. 7).

- In all simulations there is an increase in the occurrence of fires especially at higher elevations than currently because tree-dominated systems are moving uphill and warmer drier conditions are found at higher elevations under climate change conditions (Fig. 8).

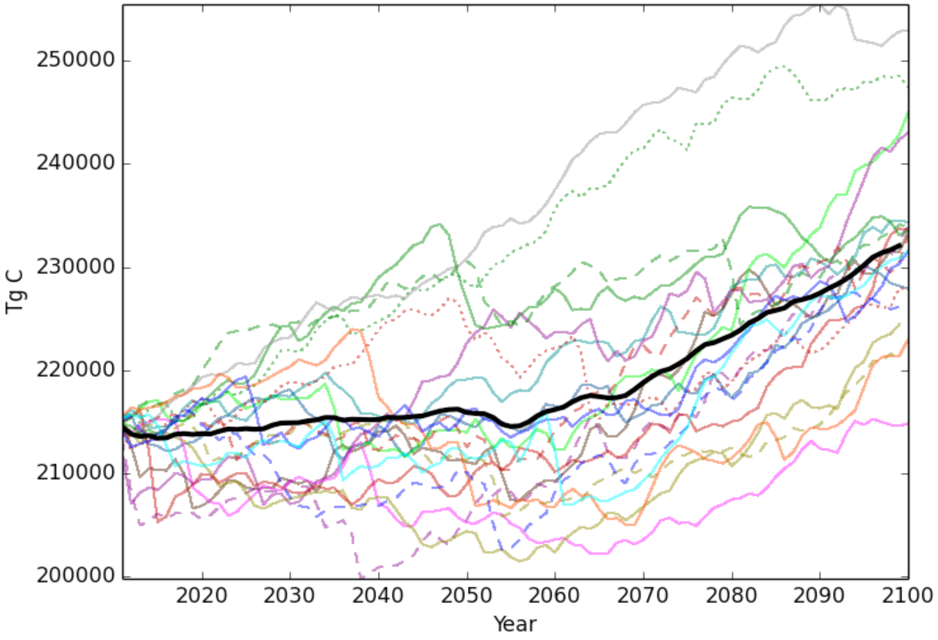

Figure 7. Total ecosystem carbon (vegetation and soil pools) in the PNW region (Oregon, Washington, Idaho and western Montana) under the RCP 8.5. Each line represents the response of the vegetation model to an individual climate future and the black line gives the mean across all future projections. Wetter scenarios cause increase in productivity as temperatures warm but also increases in fuel loads vulnerable to episodic dry years. Drier scenarios cause early drying of fuels and faster transitions to warmer land cover types. Abrupt decreases in carbon stocks shown here are caused by these simulated fire events.

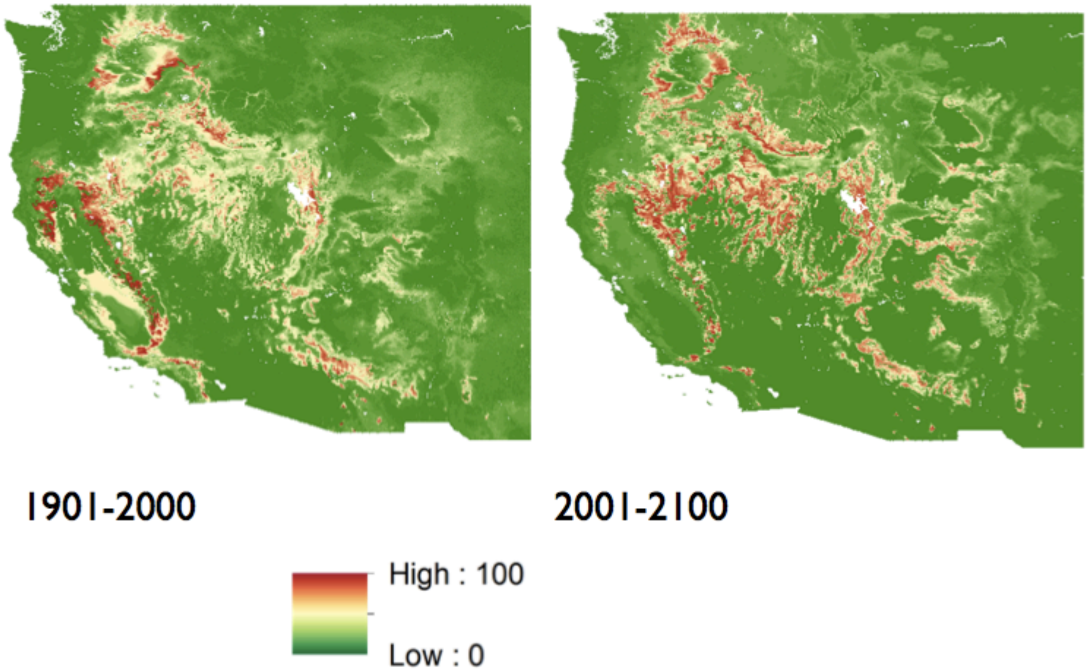

Figure 8. Comparison in the number of fire occurrences between the 20th and the 21st century. High elevation fires are more frequent in the 21st century as conditions warm.

To note: We found that the transition between historical /current conditions and fture projections was abrupt. Such fast transition to warmer conditions caused the fire model to respond quickly and simulate early 21st century catastrophic fires causing swift transitions to warmer vegetation cover types. While the overall trends are useful to consider the role of disturbance that can cause such abrupt changes it is important to keep in mind that the most important uncertainty in our results comes from the climate drivers. Early extensive fires might simply be due to artefacts in the projected climate and its large difference with current observations causing a lack of smooth transition between 20th and 21st century.

6.2.2. Forest potential productivity (3-PG)

Projected changes in productivity (given as Net Primary Production, NPP) over the western U.S. for one climate scenario (MIROC5 RCP8.5) show large increases at high elevations and in the intermountain West but decreases along the West coast (Fig. 9). Projections of the distribution of Douglas-fir from the 1990s to both the mid- and late-21st century, also for the same climate scenario, show declines in its warmer southern limit but large increases northward (Fig. 10). Climate change in the MIROC5 scenario is of intermediate intensity in terms of change in mean annual temperature. Results from the other climate scenarios showed similar trends with a magnitude that corresponded primarily to the shift in mean annual temperature.

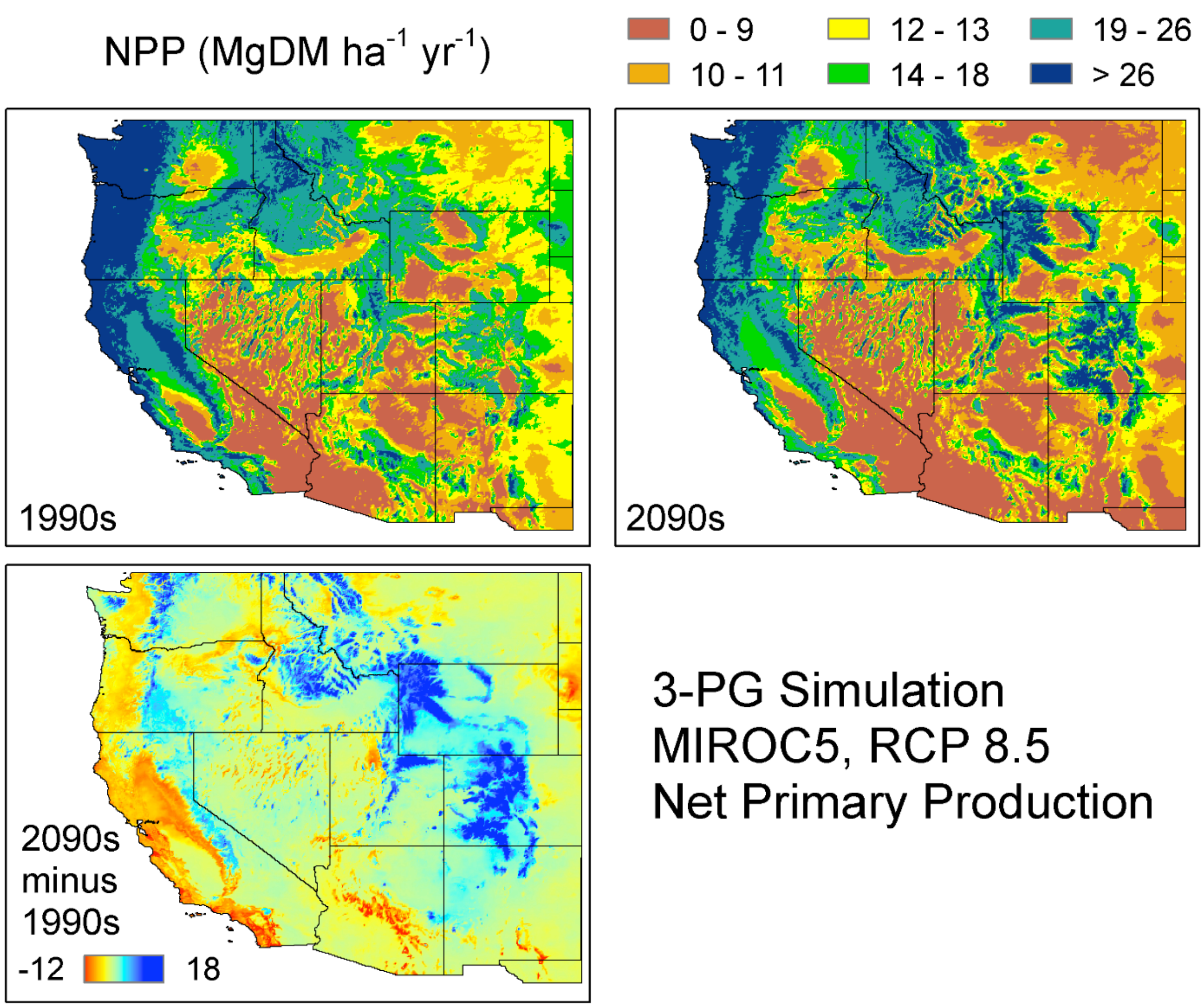

Figure 9. Forest potential productivity based on 3-PG model simulations and the MIROC5 RCP 8.5 climate scenario. The upper panels are potential productivity in the 1990s and 2090s. The lower panel is the change in forest productivity between the 1990s and 2090. Blue tones indicate increases in productivity. The model was run on all 4 km grid cells independent of whether or not forest cover was currently supported.

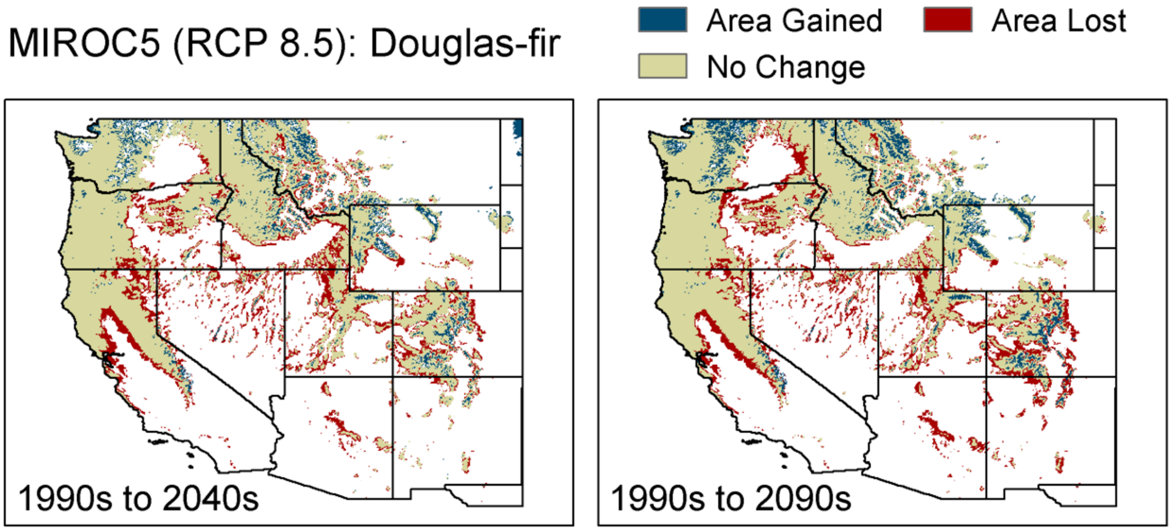

Figure 10. Projected changes in the distribution of Douglas-fir by 2100 using the MIROC5 RCP8.5 scenario.

6.3. Hydrology

In the PNW, losses in snow aereal extent and snow water equivalent (SWE), as represented by our VIC simulations, will intensify in the 21st century, with the latter decreasing by nearly 30% by mid-century and by 40-50% by late-century (Fig. 11). Future losses of April SWE will be substantially greater than losses in colder winter months (i.e. February, shown in Fig. 12). Furthermore, these losses will be more severe in lower-elevation/transient-snow zones, with large losses in the Oregon Cascades and mountain ranges of central and northeastern Oregon. With earlier initiation of snowpack melt, water that was formerly stored over-winter as snowpack will increasingly flow as river discharge in the winter and spring months (Fig. 13). Diminished summer streamflow will result, and in these months of peak water demand for irrigation and fish-flows, greater resource management and allocation challenges will arise.

Mean annual flows will not change greatly in magnitude, but increases in cool season runoff will be balanced by decreases in warm season runoff. Small precipitation increases in the cool season may enhance high-elevation snowpack but appear to do little to preserve mid-elevation snow; spring soil moisture increases are likely due to precipitation becoming increasingly and generally more comprised of rainfall (than snow) and by snow becoming more transient (freeing water to transit through the soil column).

August soil moisture west of the Cascades and in higher elevations to the east that are snow-affected show decreases of greater than 10% (Fig. 14). In the high plateau and desert of eastern Washington, eastern Oregon, and southern Idaho (where winter snow accumulations both historically and in the future are small), August soil moisture increases slightly, in line with increased winter and spring precipitation, although practical implications may be modest. These increases are relative to relatively low available moisture in the historical period, and still result in seasonally low soil moisture. It is unlikely that the need for irrigation will diminish, for instance, although these changes may (depending on other factors, such as fuel ignition) have implications for wildfires.

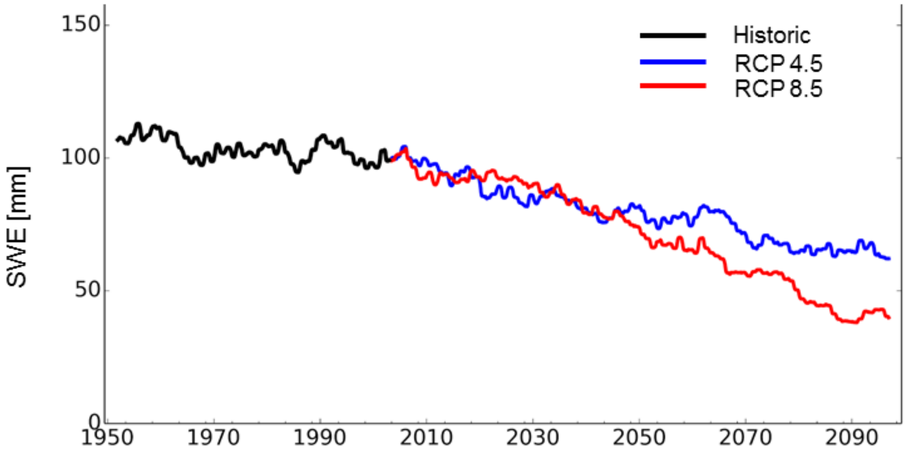

Figure 11. 10-model ensemble average SWE monthly time series averaged over Western U.S. domain (5-year moving average).

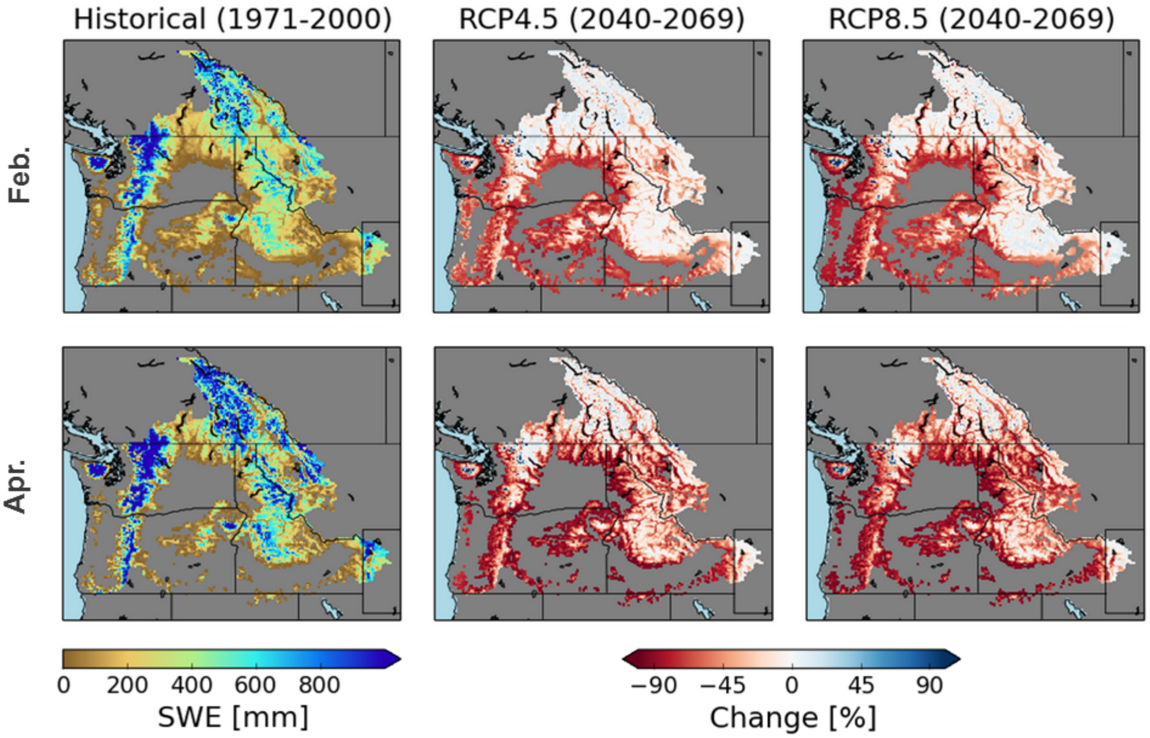

Figure 12. February (top) and April (bottom) mean snow water equivalent (SWE) and percent change from historical period for 10-model ensemble average. Cells with mean SWE less than 10 mm not plotted and excluded from change analysis.

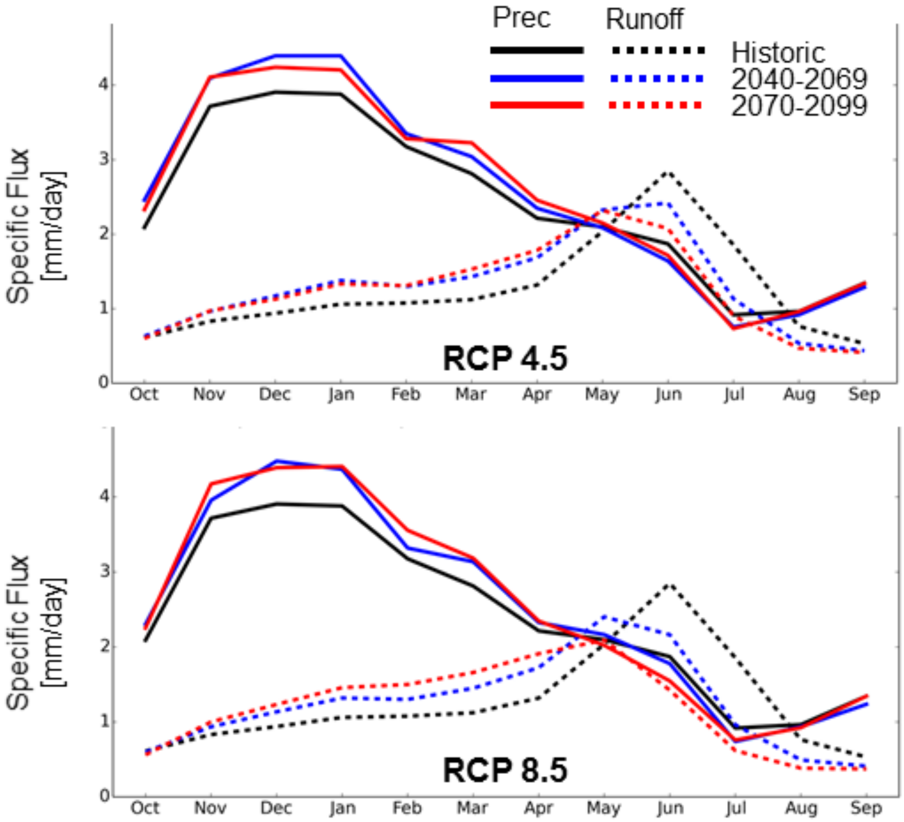

Figure 13. 10-model ensemble average monthly precipitation and total runoff climatologies (30-year epochs) for Columbia Basin upstream of The Dalles, Oregon.

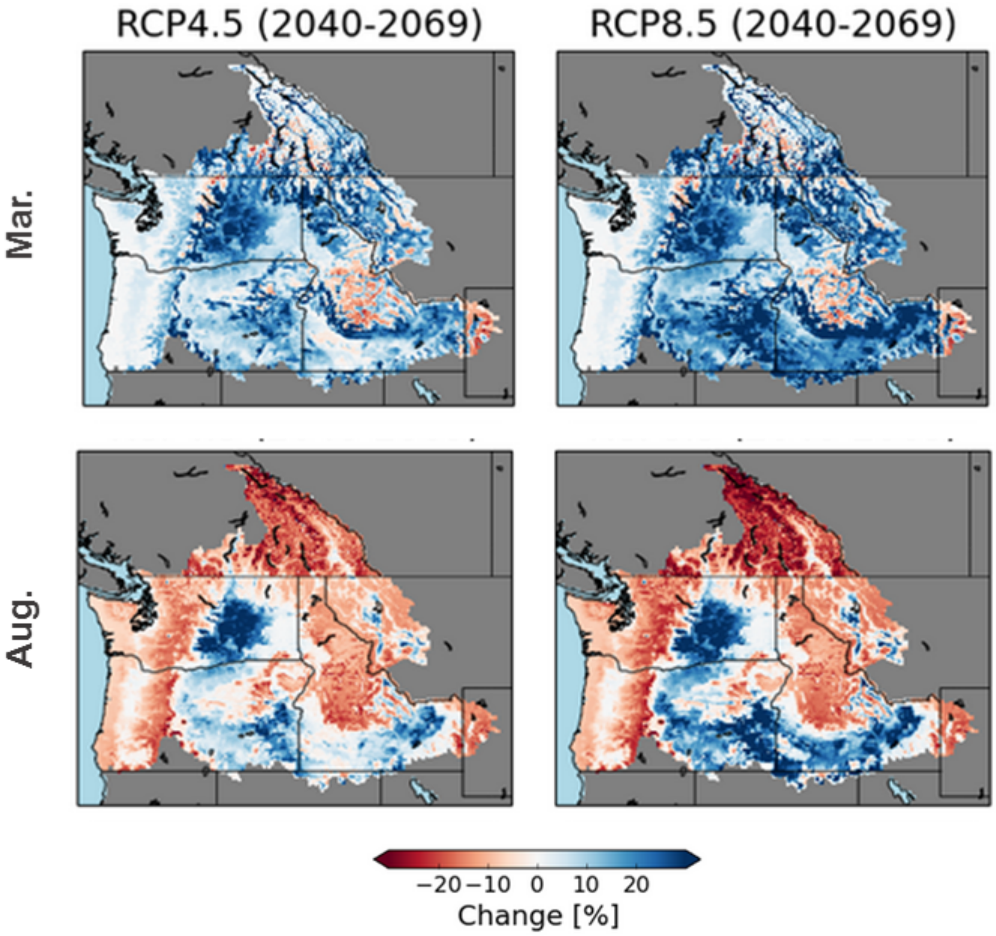

Figure 14. March (top) and August (bottom) average soil moisture percent change relative to historical period (1971-2000) for 10-model ensemble average.

7. ANALYSIS AND FINDINGS

Describe your research findings and list major discoveries, innovative approaches and solutions, and accomplishments made by the project team.

7.1. Climate

7.1.1. Evaluation of global climate model regional performance

The determination of which GCMs are "better" than others hinges on which metrics are used to evaluate the GCMs. Despite this challenge, our assessment was able to identify GCMs that performed poorly in many aspects, providing for a basis for favoring certain GCMs over others when necessity dictates that a small number of GCMs are used to develop scenarios for climate impact assessments. Because the CMIP5 GCMs did not perform substantially better then CMIP3 GCMs, this implies that results from previous climate impacts analyses using CMIP3 data should not be discounted.

7.1.2. Statistical downscaling of global climate simulations

The downscaled climate data utilized for the hydrology teams was analyzed through maps and made available on our website (http://maca.northwestknowledge.net). Spatial maps of biases of the historical downscaled data from the training dataset for each of the variables showed that biases (downscaled historical runs compared to observed data) were within expected tolerances over the entire contiguous USA for all the models. Spatial maps of projected changes for each of the variables from the downscaled data were compared to that from the raw GCM data and were found to be in rough agreement over all the models. Time series for a few select stations over the western USA were examined from the downscaled data and compared to the raw GCM data and found to be in rough agreement over all the models.

7.1.3. Regional climate modeling for the PNW

The regional climate model simulated a strong connection between the rate of warming and the region's topography. This was particularly apparent in the spring when the winter snowpack was melting/ablating. The decrease in snow cover as the air temperature increased into the future decreased the surface albedo, leading to yet higher air temperature. The impact would be significant to both water resources management and species migration. In the first case, it implies even less snow storage in the mountains with time, and in the second case, it may mean species must move even higher in elevation towards climates to which they are historically adapted.

Simulating this positive feedback illustrates the strength of dynamical downscaling, as this type of dynamic mechanism is simulated poorly, if at all, at the regional scale by GCMs because they lack the necessary spatial resolution. Statistical downscaling methods that do not explicitly consider such feedbacks (and none of the established methods do, as far as we know) will not be able to incorporate these feedbacks.

The novel super-ensemble regional modeling approach allowed us to unambiguously identify the relationships between changing temperature, elevation, and loss in SWE. This is because the very large number simulations allowed us to clearly identify the climate change signal from the internal variability (i.e. noise) of the climate system by effectively smoothing out the internal variability.

7.2. Vegetation

7.2.1. Potential vegetation (MC2)

Climate futures from GCMs versus ESMs from the same climate modeling team (e.g. MIROC5 vs. MIROC-ESM; Fig. 14) are sufficiently different that the vegetation model produces different vegetation responses. This was the first time we could document this result. Similarly, different model versions (HadGEM2-CC vs. HadGEM2-ES) produce different futures that cause different vegetation responses (not shown here). Through this exercise, the uncertainty due specifically to climate inputs is thus clearly emphasized.

While all climate models project warmer conditions, they differ in their projections of the seasonality and magnitude of rainfall. The MC2 model is sensitive to the water available for plant production and soil organic matter decomposition, but also for fuel-build up and wildfire occurrence. The resulting complex interactions of climate, vegetation growth and disturbance drive the large changes the model is simulating with much geographic patchiness due to soil types as well as temporal variability due to changes in rainfall seasonality. This is an important conclusion about the need for vegetation models to include disturbance when projecting more realistic future conditions.

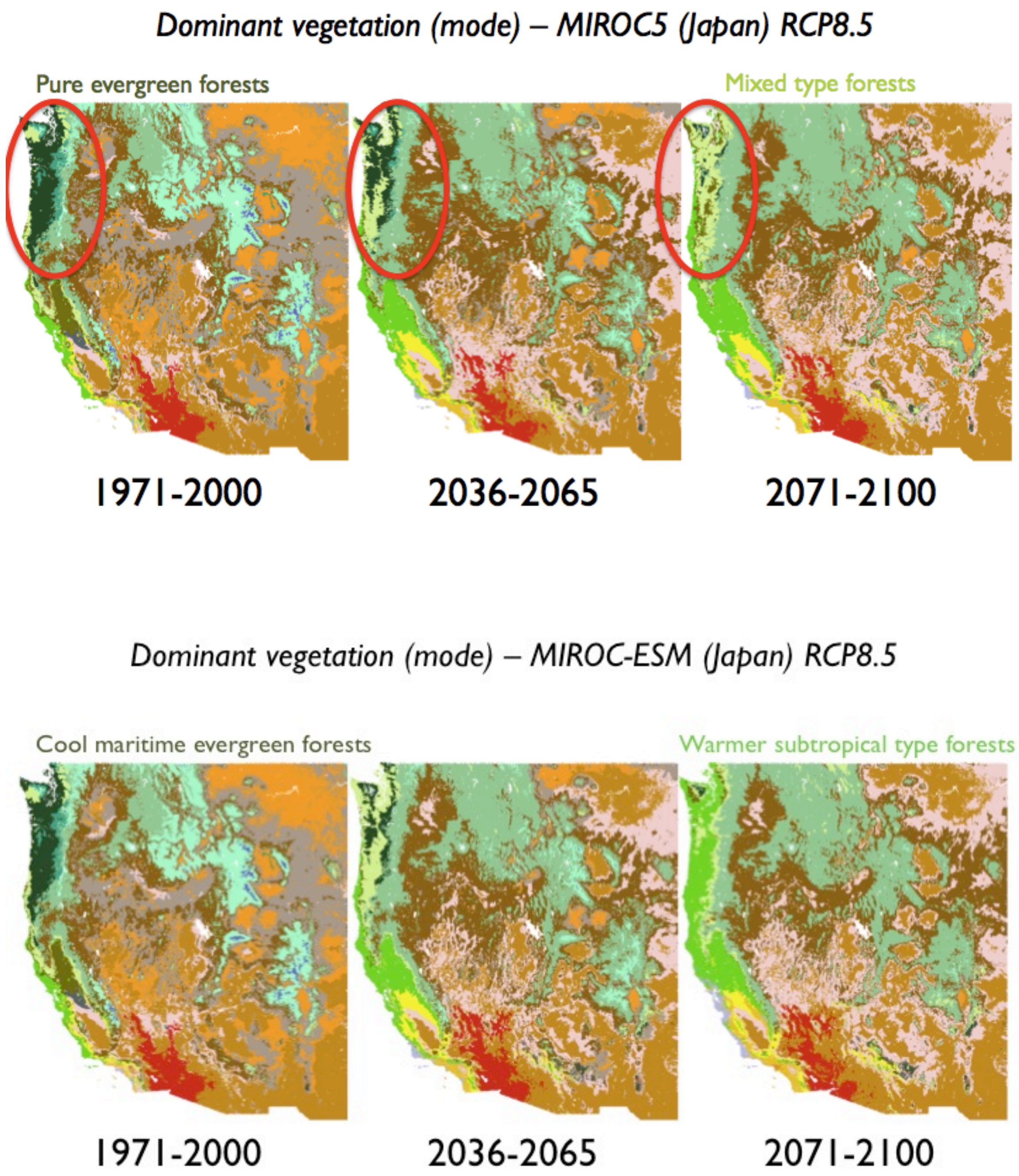

Figure 15. Potential vegetation distribution (most frequent vegetation type in a 30 year simulation) using (top) MIROC and (bottom) MIROC-ESM future climate. Disturbance such as fires allow for faster transitions to warmer vegetation types. Increases in precipitation under warmer conditions promotes the transition from evergreen dominant to mixed hardwoods type forests.

7.2.2. Forest potential productivity (3-PG)

The 3-PG vegetation modeling suggested that forest productivity in the Pacific Northwest is likely to increase at relatively high elevations (associated with a lengthening of the growing season), and decrease at low elevations (as a function of greater evaporative demand and increased soil drought). However, hydrological studies (e.g. Tague et al. 2008) have shown that high Cascades conditions may not allow widespread expansion of forests due to high evaporative demand and reduced water resource availability. Our study highlighted the need for a better integration between hydrological simulations of soil water availability and vegetation modeling. Given the caveats, there was a general consistency among the 3 CMIP5-MACA scenarios examined in terms of the spatial pattern of NPP increases and decreases. The distribution of Douglas-fir is expected to be shifted upslope and northward in the Pacific Northwest.

7.3. Hydrology

In the PNW, our findings align in general context with those of prior studies. These include losses in snow aerial extent and snow water equivalent, greater losses in lower-elevation/ transient-snow zones (particularly in Oregon), earlier snowpack melt, decreased summer streamflow, and little change in annual flows. Our research incrementally improves upon that of prior studies by using more sophisticated model forcing data (MACA downscaling), includes the latest GCM predictions (from CMIP5), uses two hydrologic models (rather than one), and produces output that is more readily analyzed using standard data archiving protocols (NetCDF).

8. CONCLUSIONS AND RECOMMENDATIONS

Discuss the results of the project and what you found out. Did you encounter any problems during the project? What project tasks were not completed and why? What would you do differently if you did this project again? Also state and describe the recommended next steps. Based on what you've learned, what do you think should be studied next?

8.1. Climate

Generation of the climate data to meet the needs of particular users was challenging. For this project, we had 2 direct users (the vegetation models and the hydrology modelers). Each group had particular and different needs in terms of the spatial and temporal resolution of the data, and the gridded domain. Because the hydrological modeling required the Canadian portion of the Columbia Basin, an entirely distinct set of downscaled data using a new, and untested, observational "training" dataset was required. This more than doubled the work for the climate team, because it required both creating a second set of data and troubleshooting the new observational training data.

8.2. Vegetation

A problem encountered with the input climate data required that all MC2 and 3-PG simulations be done twice. A second problem (precipitation values zeroed for every month for the last year of the historical period) was discovered too late for a complete re-run and assumed to be of minimal consequence for the overall results. The vegetation model simulates vegetation cover resulting from a legacy of past climate conditions. While the MACA projections provided historical climate data, the discrepancy between observed climate (provided by PRISM) and the projections was such that simulations of the end of the 20th century would have been unrealistic. Results shown here are also highly uncertain because the the large discontinuity in temperature and moisture regimes between provided futures and the PRISM time series causing our model to simulate fires as conditions abruptly change to significantly warmer and drier ones.

We will be obtaining from USGS colleagues CMIP5 landuse scenarios, which will allow us to simulate actual vegetation with the MC2 model using CMIP5 climate futures. We are seeking funding to continue the exploration of the sensitivity of the vegetation model to the different types of drivers and the development of smoother more realistic transitions to projected futures.

We are also seeking funding to further develop web tools to not only display project results but to provide analysis and decision support tools (e.g. to generate climate-related indices - climate refugia or hotspots, summarize vegetation responses and fire risk by user-determined unit of choice) for managers and policy makers seeking usable climate change information.

The 3-PG modeling approach represents an alternative to purely statistical approaches to evaluating climate driven changes in forest productivity and species distribution. Notably it can account for no analogue climates of the future. Limitations of the 3-PG simulations was first that ecophysiological effects of increasing CO_2 concentration were not accounted for. High CO_2 may be associated with increased water use efficiency (Keenan et al. 2013) and thus could significantly ameliorate impacts of increasing vapor pressure deficits and reduce the incidence of summer soil drought. Secondly, the model did not account for the genetic adaptive capacity of the species across its range and the likelihood of adaptation of climate change. In our study of vegetation response,the models we used lacked a daily time step which would have allowed more robust representation of carbon and water fluxes through the soil-plant continuum by responding more realistically to climate extremes.

8.3. Hydrology

Our findings are generally consistent with those of previous studies of the future hydrology of the Western U.S. based on CMIP3. The signature of extratropical drying is muted somewhat in the CMIP5 results, and this is reflected in our hydrologic projects (note that this is more important in the western interior, e.g., the Colorado River basin, than for the PNW).

As in previous studies, the main signature of climate change on PNW hydrology is reduced snow, which affects the timing of streamflow (primary), and soil moisture (wetting in winter/ early spring, drying in summer in snow-dominated watersheds, although the low elevation eastern interior shows slight increases in summer soil moisture due to increased winter and spring precipitation. Annual streamflow volume changes are small averaged over models – in our projections there appears to be a rough balance of increased precipitation and increased evapotranspiration.

Collaboration and inter-exchange of knowledge and resources between partners was very beneficial to increasing data quality and technical capacity. Greater clarity regarding data archiving requirements and archiving assistance would be very helpful.

9. MANAGEMENT APPLICATIONS AND PRODUCTS

Describe how you expect your study findings to be used in the management of natural or cultural resources. What managers, administrators, and decision makers did you work with during the project? Please include names, agencies, and their roles in the study (e.g., advisor, aided with project design, contributed data, tested a decision support tool). What decision support tools were developed through your study? To the best of your knowledge, what specific resource management decisions will be made or improved upon because of the results and/or products of this research?

9.1. Climate

In addition to downscaling the climate datasets, we have created a web interface for potential data users to learn more about the methodology and visualize some of the datasets through http://maca.northwestknowledge.net. On this website, we provide detailed information on the MACA method and dataset, guideance on the usage of downscaled climate dataset and several visualization tools. The visualization tools include the ability for users to examine spatial patterns of change for the variables that have been downscaled. These decision support tools are utility both for direct users of the climate datasets as well as for general depiction of projections across the region. Users can examine similar visuals across seasons, variables and scenarios on the web site. Users can also visualize time series of downscaled and raw GCM output for specific locations as well as examine projected changes in extremes represented by the downscaling and query the magnitude of any biases inherited from the downscaling.

9.2. Vegetation

CBI will make climate and vegetation model results available through conservation atlases for the LCC regions (funding independent from this project) included in the project domain on databasin.org. CBI is also using results from this work for ecological analysis in the Sonoran and Mojave area of southern California as part of the Desert Renewable Energy Conservation Plan.

9.3. Hydrology

Our data on the hydrological and land surface energy budget will be useful to a range of federal, tribal, and state agencies, and for-profit and non-profit entities engaged in climate change assessments. The full and summary datasets we have produced and archived in standardized, self-describing NetCDF format will greatly aid users in applying our results across diverse applications.

10. OUTREACH

List the type of outreach that you did, or expect to do, including any publications or other presentations of your project to the public. Include a list of articles that emerged from this research. The list should include articles in preparation, under review, accepted, or published in peer reviewed journals and other non-peer reviewed journals. Also list project-related conference presentations, seminars, webinars, workshops, and other presentations to the public made by research team members. Describe how the study results were or will be communicated to managers and decision-makers.

10.1. Visualization, sharing and distributing summary results

1. We have continued to update our climate data webpage (http://maca.northwestknowledge.net) to provide visualizations, data, and guidance on how to use the climate data.

2. We provided customized climate datasets and advice to approximately 30 scientists with small geographical regions of interest within the Western USA.

3. We built a web site to illustrate the downscaled climate scenarios and MC2 time series results summarized by ecoregions: http://consbio.webfactional.com/integratedscenarios/

4. We created a databasin.org group for the Integrated Scenarios Project to share mapped summaries from the vegetation and hydrological results as well as climate inputs: http://bit.ly/1jz0DbK

6. Two papers have been published to date in peer-reviewed scientific journals and at least 6 more are in preparation or have been submitted. Sixteen presentations were given at conferences

and workshops in the Pacific Northwest and 6 more presentation will be given at the upcoming 5th Annual Pacific Northwest Climate Science Conference.

10.2. Publications

Submitted or in preparation

Bachelet, D., T. Sheehan, D. K. Ferschweiler, J. Abatzoglou, K. Hegewisch. Simulating vegetation change, carbon cycling and fire over the western US using CMIP5 climate projections. In preparation.

Li, S., P. W. Mote, D. Vickers, D. E. Rupp, R. Mera, M. R. Allen, R. G. Jones. Evaluation of a regional climate modeling effort for the western US using a superensemble from climateprediction.net. In preparation for *Journal of Climate*.

Mote, P. W., M. R. Allen, R. G. Jones, S. Li, R. Mera, D. E. Rupp, A. Salahuddin, D. Vickers. Superensemble regional climate modeling for the western US. Submitted to *Bulletin of the American Meteorological Society*.

Rupp, D. E., J. T. Abatzoglou, P. W. Mote. Diagnosing CMIP5 21st century precipitation projections for the Pacific Northwest. In preparation for *Journal of Geophysical Research: Atmospheres*.

Sheehan, T., D. Bachelet, K. Ferschweiler; J.T. Abatzoglou, K. Hegewisch. Ecoregional projections for the Pacific Northwest using CMIP5 climate projections. In preparation.

Turner, D. P., N. Coops, N., D. Sharp. Assessing 21st Century changes in forest productivity in the Pacific Northwest. In preparation for *Climatic Change*.

Vano, J. A., D. E. Rupp, J. B. Kim, P. W. Mote. Selecting climate change scenarios using impact-relevant sensitivities. In preparation for *Geophysical Research Letters*.

2014

Abatzoglou, J. T., D. E. Rupp, P. W. Mote. 2014. Seasonal climate variability and change in the Pacific Northwest of the United States. *Journal of Climate*, (27), 2125-2142, doi:10.1175/JCLI-D-13-00218.1.

2013

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. *Journal of Geophysical Research: Atmospheres (118)*, 10,884-10,906, doi:10.1002/jgrd.50843.

10.3. Presentations

Upcoming

Abatzoglou, J. T, R. Barbero, S. Larkin, D. McKenzie, E. A. Steele, D. Bachelet. Will climate change increase the occurrence of very large fires in the northwestern United States? 5th Annual Pacific Northwest Climate Science Conference, Seattle, WA, Sep. 9-10, 2014.

Hegewisch, K, J. Abatzoglou, D. Rupp, P. Mote. Statistically downscaled climate data using the Multivariate Adaptive Constructed Analogs approach. 5th Annual Pacific Northwest Climate Science Conference, Seattle, WA, Sep. 9-10, 2014.

Lettenmaier, D., M. Stumbaugh, B. Nijssen. Integrated Scenarios Project: Estimates of future changes in western U.S. hydrology. 5th Annual Pacific Northwest Climate Science Conference, Seattle, WA, Sep. 9-10, 2014.

Rupp, D., J. Abatzoglou, K. Hegewisch, P. Mote. New views on future Northwest climate. 5th Annual Pacific Northwest Climate Science Conference, Seattle, WA, Sep. 9-10, 2014.

Sheehan, T., M. Gough, D. M Bachelet, J.T Abatzoglou, K. Hegewisch. Climate, forest vulnerability, carbon stores and fire: delivering western US projections via the web. 5th Annual Pacific Northwest Climate Science Conference, Seattle, WA, Sep. 9-10, 2014.

Vano, J., D. Rupp, J. Kim, P. Mote. Selecting climate change scenarios using impact-relevant sensitivities. 5th Annual Pacific Northwest Climate Science Conference, Seattle, WA, Sep. 9-10, 2014.

2014

Abatzoglou, J., K. Hegewisch, P. Mote. Climate data user's guide, Integrated Scenarios of the Future Northwest Environment Workshop, Portland, OR, April 17, 2014. http://youtu.be/KnG4_Cc_VL8

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