Proposal for a Pacific Northwest Climate Modeling Consortium

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Project Summary

The consequences of climate change will be felt increasingly over the coming century. Robust planning decisions need to be made with the best available projections of future climate change, which will vary substantially around the world. It is well established that some applications require explicit modeling of local-scale changes in climate using a regional climate model, as opposed to the widely available statistical approaches that are typically used to "downscale" coarse global climate model simulations. To date, regional climate model simulations for the Northwest have been used in a range of applications with proven success and value. Nevertheless, the work in regional modeling has been piecemeal, without broad coordination between scientific research, model development, and regional impacts applications. Furthermore, due to the limited suite of simulations available to date and the lack of a systematic approach in generating regional simulations, robust probabilistic predictions of future regional climate have not been available. Far better information is required to guide adaptation planning in the region.

We propose to build on the existing regional modeling capacity in the Northwest to develop a broad suite of regional climate projections for the western U.S., based on regional dynamical downscaling of multi-model global climate simulations, completed at a resolution appropriate for impacts applications and scientific research. The effort will be iterative, building on evolving science questions, stakeholder vulnerabilities, and model capabilities. The research team has long-standing collaborations and expertise in regional climate model research and impacts applications. As demonstrated by consortia supporting regional weather and air quality modeling, long-term collaborations between a highly interested user community and a dedicated research effort can produce highly useful environmental guidance that benefits all.

Introduction

Concerns over the effects of climate change in the northwestern United States have increased rapidly during the past decade, reflecting climate research that suggests substantial impacts during the current century. In response, government agencies and resource managers have begun evaluating their vulnerabilities, developing adaptation plans, and implementing measures to reduce society's exposure to the risks posed by climate change. For long-term infrastructure investments, decisions are being made today for structures and facilities that will be in place for 50-100 years, by which time the climate will have changed substantially. Wise and cost effective decisions require state-of-the-science predictions of the future regional climate of the region.

The impacts of climate change will not be distributed evenly around the globe or in the Pacific Northwest: changes will vary from region to region and different areas will be more or less vulnerable to evolving climate. One of the great scientific challenges of this century is to develop improved projections of regional climate, with a focus on science that is actionable – i.e., predictions that advance our ability to make robust decisions

A variety of powerful modeling and statistical tools have been developed in the research community to predict future changes in regional climate and to link these changes to regional impacts. In particular, significant advances have been made in Regional Climate Models (RCMs), which encompass atmospheric, land-surface hydrology, and coastal ocean/estuarine components of the regional earth system and their mutual interactions. The value of regional climate projections is further increased by powerful new tools for statistical post-processing.
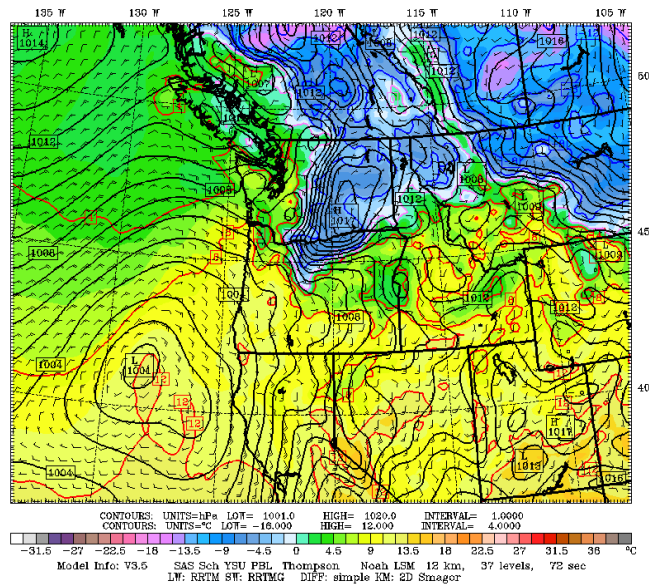
Several research groups have implemented high-resolution regional climate models and simulated the future climate by driving these models with output from Global Climate Models. In our region, collaborative research at the University of Washington and Washington State University has developed the capacity to simulate future climate over the region at high spatial resolution and apply these projections to simulate the impacts of climate change on air quality (Avise et al, 2012), flood risk (Salathé et al, 2014), agricultural processes (Liu et al, 2014), estuarine processes (Moore et al, 2015), and drought (Gao et al, 2012). These regional projections provide enhanced insights into critical local environmental issues, such as expected changes in snowpack, flooding and heavy precipitation, coastal ocean pH and oxygen levels, and renewable energy availability, to name a few.

Until now, the potential for substantially improved climate projections, geared towards quantifying decision-relevant impacts, has not been fulfilled due to a lack of resources and coordination. The proposed consortium will take on this challenge, creating a coordinated regional climate research program supported by a collection of local, state, private sector, and national stakeholders.

The Northwest Climate Modeling Consortium

We propose the formation of a **Northwest Climate Modeling Consortium** (NCMC). The goal of this consortium will be to support the creation and dissemination of actionable information regarding the regional implications of global climate change. Specific goals include:

1) Develop an ensemble of regional climate simulations over the western U.S. (the exact domain will be determined in coordination with consortium members, but will at a minimum include Washington, Oregon, northern California, and associated coastal waters)

High-resolution forecasts have been made for nearly two decades by the Northwest Modeling Consortium

2) Improve regional modeling capabilities through new efforts to validate and optimize models, apply sophisticated post-processing, and by facilitating model coupling, both to GCMs and other models (e.g., land surface, ocean, air chemistry).
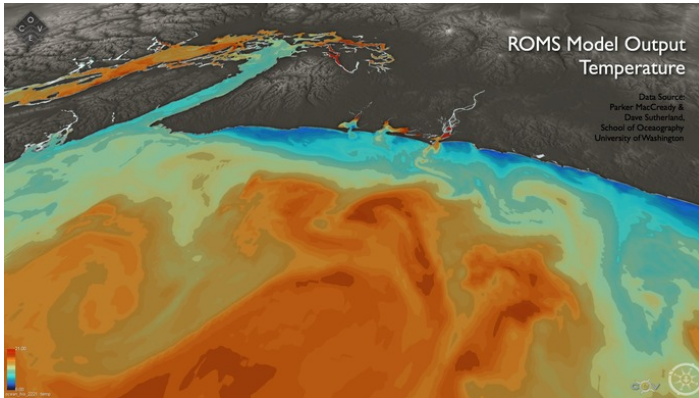
3) Enhance linkages between regional climate modeling efforts and the technical and management activities of agencies and governments in the region.

4) Establish priorities and coordinate funding for relevant applied climate research associated with regional climate modeling in the region.

Successful prototypes exist for the proposed regional climate consortium concerning related applications: weather and local air quality prediction. Specifically, the Northwest Modeling Consortium and NW AirQuest consortia have provided environmental prediction and decision support for short-term (up to 7 days) weather and air quality over the Northwest. In these and other efforts, the WRF (Weather Research and Forecasting) atmospheric model has been coupled to a regional air quality model (CMAQ: Community Model for Air Quality), a coastal ocean model (ROMS: Regional Ocean Modeling System), and a distributed hydrological model (DHSVM: Distributed Hydrology Soils and Vegetation Model), all in real-time. The NW Modeling and AirQuest consortia, in place for nearly two decades, have demonstrated that a collection of national, regional, and local entities, including government, education, and the private sector, can join together to plan, support, and effectively utilize advanced prediction technologies that no single entity has the resources to take on alone. It has also demonstrated the value in coupling a range of environmental modeling systems.

The proposed consortium will support the building and use of an integrated regional climate modeling system, which in turn will be driven by output from a collection of global climate models, such as the recently completed CMIP-5 (Coupled Model Intercomparison Project, Phase 5) global atmosphere/ocean simulations forced by a variety of greenhouse gas scenarios, as well as reanalysis fields available from several national centers. The proposed effort will build upon the substantial research investment made by a number of agencies and local governments that

ROMS Model Output
Temperature

Data Source:
Parker MacCready &
Dave Sutherland,
School of Oceanography
University of Washington

The coupling of the WRF atmospheric model with the ROMS coastal ocean model has already been completed successfully for contemporary periods.

have created a foundation of modeling technology and understanding of regional climate issues (see the appendix for some examples).

The regional climate model system will encompass five primary components:

1. A regional atmospheric model, such as the *Weather Research and Forecasting (WRF)* model.

2. A land surface model, such as the *Community Land Model (CLM)*

3. A hydrological processes model such as the *Variable Infiltration Capacity (VIC)* model, *WRF-hydro*, *DHSVM*, or *the Regional Hydro-Ecologic Simulation System (RHESSys)*.

4. A coastal and estuarine processes model such as the *Regional Ocean Modeling System (ROMS)*.

5. A regional air quality model such as *CMAQ or WRF-Chem*

Significant effort and investment in regional climate modeling over the western U.S. has already taken place, including programs at the University of Washington, Washington State University, Oregon State University, and the Pacific Northwest National Laboratory. These regional climate-modeling efforts have simulated the current climate of western North America and completed a limited number of projections for the region on time scales of decades to a century. This work has developed and validated the basic modeling approach described above, including the linking of WRF to land, ocean, and air quality models, and supported climate impacts studies at a handful of agencies (see references below). However, the results of this work should be viewed as exploratory: they do not include a sufficiently large number of regional climate simulations for estimating forecast uncertainties, and lack the sophisticated statistical post-processing required to provide robust probabilistic projections of 21st century regional climate changes.

The Essential Technology: Dynamical Downscaling of Global Climate Models

Nearly two-dozen international research groups are now running Global Climate Models (GCMs) driven by a variety of greenhouse gas scenarios. These models include atmospheric, ocean, and land-surface components and are typically run for periods of 100 to 150 years, covering both a contemporary period and most of the 21st century. Such models sample a wide range of initial states, physical models, and computational approaches, providing insights into the uncertainties of extended climate prediction. Unfortunately, such models require substantial computing resources, and are typically limited to a coarse spatial resolution of 100 to 150 km (about 60 to 90 miles). To illustrate the effects of this coarse topography, the terrain of one global model is shown below (left panel; the NCAR Coupled Community System Model 4 (CCSM4), used in CMIP-5). Critical regional features do not appear at such coarse resolution (e.g., the Cascade and Olympic mountains), and the coastline is poorly resolved. A number of studies (e.g., Mass et al. 2002) have shown that a horizontal grid spacing of approximately 12-km is needed to realistically simulate the regional weather and climate features of the western U.S.. The right panel shows the terrain from the WRF model with 12-km grid spacing, which clearly resolves most of the major mountain ranges and coastal features of the region.
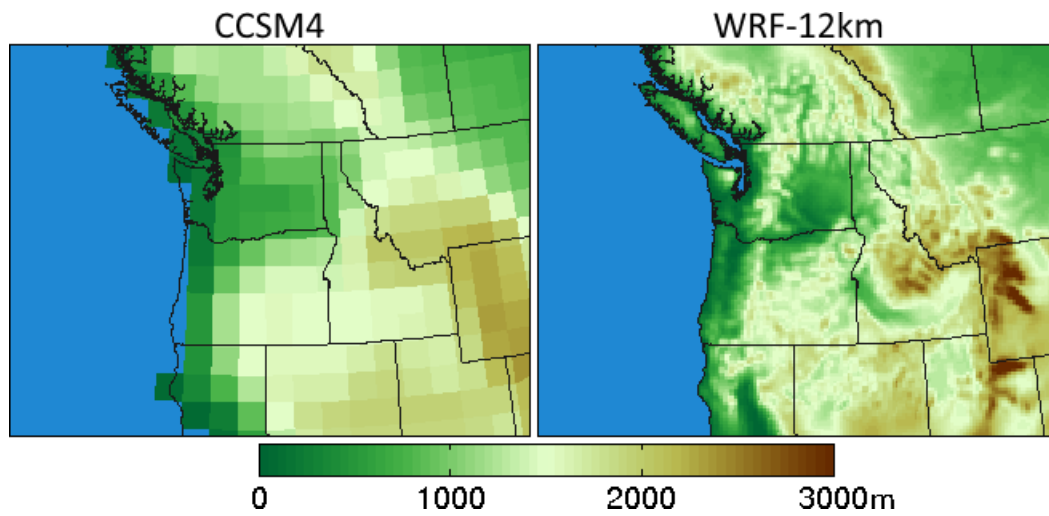

A widely applied approach to localizing global climate model projections for climate impact studies is known as "statistical downscaling". Here global climate model output is "mapped" to local climate change based on historical relationships. The value of the resultant climate projections is limited because statistical downscaling considers neither local regional environmental processes nor how these processes change as the planet warms. For example, if thunderstorms became more frequent under global warming and changed the regional distribution of precipitation, statistical downscaling would be unable to add this change to the projections. A superior approach for determining the local implications of global climate change in complex environments like the Pacific Northwest is the use of a regional climate model to "dynamically downscale" global model output.

In a regional climate modeling using *dynamical downscaling*, high-resolution, full-physics, atmospheric, ocean, and land-surface/hydrologic models are run over a subdomain of a global model, the global model providing boundary conditions for the smaller domain. These regional models can be run at higher resolution than global models and thus can consider local and

regional features and simulate changing local interactions and processes within the coupled climate system. Computer resource demands are more modest than running high resolution everywhere because the high-resolution domain is relatively small.

This dynamical downscaling approach has been developed over the past twenty years, but only recently has the technology developed to the point of providing demonstrable value over statistical downscaling. As an example, changes in 2-m temperature computed from a coarse resolution model versus those from a regional model (Salathé et al. 2010) are shown below. The left panel shows the simulated change in winter surface air temperature between 1995 and 2050 from the ECHAM-5 global model. Temperatures are warming, but the patterns are unrealistically smooth due to the poor representation of the actual terrain. In contract, the right panel shows the results obtained by dynamically downscaling the global model output using a high-resolution regional model (MM5, the 5th generation Penn State/NCAR mesoscale model), implemented at 12-km grid spacing. In both cases, warming is amplified by the snow albedo feedback, as snowpack is lost and the surface absorbs more sunlight. The results are substantially different, however, with major impacts from regional terrain including bands of enhanced warming caused by melting snow on the slopes of major topographic features. Such an effect cannot be represented by statistical downscaling methods since statistical approaches do not represent the physical processes responsible for this feedback.
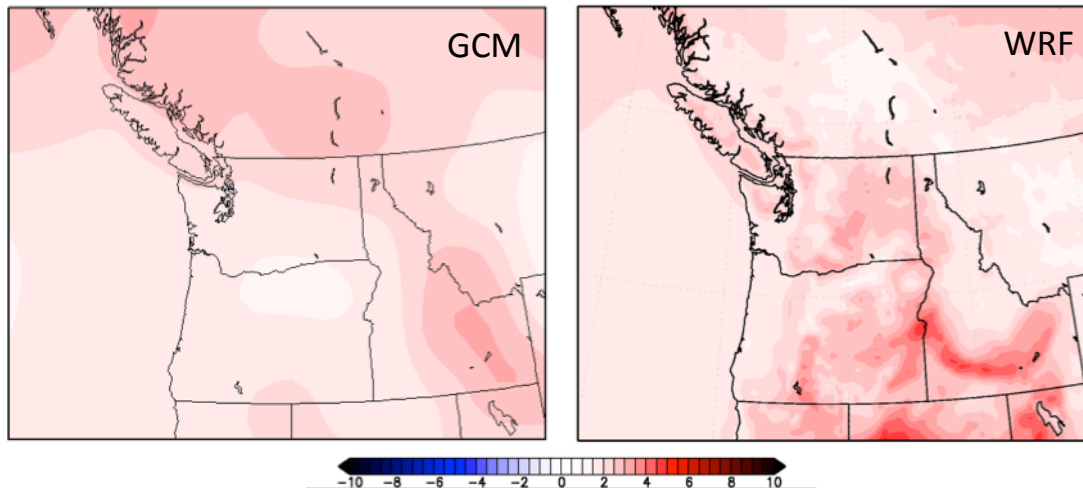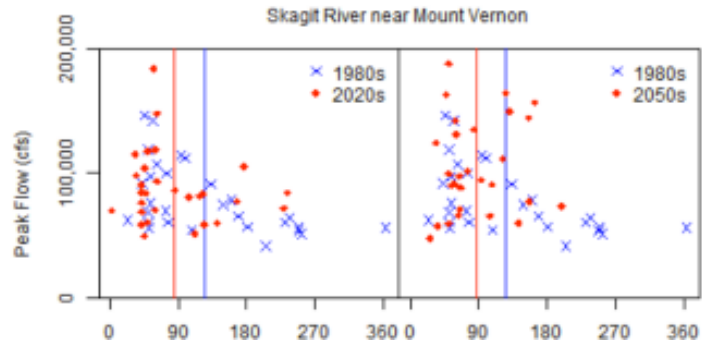

Global models (left panel) simulate an artificially smooth pattern of warming in the Northwest, whereas regional models (right panel) capture the effects of terrain on warming. Both maps show the change in Dec-Feb minimum temperatures from 1995-2050, based on the ECHAM-5 GCM and a medium (A1b) greenhouse gas scenario
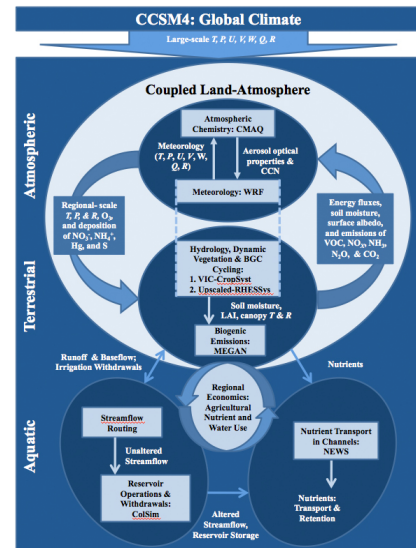
Dynamical downscaling can extend beyond a regional atmospheric model by including regional ocean, hydrologic, air quality, and land-surface models as well. Substantial exploratory work has already been completed over the western U.S. for several coupled regional climate simulations. For example, an ECHAM-5 global model simulation for 1970-2070 was used to drive a 12-km WRF simulation over the same period, which in turn provided input fields for the VIC hydrological model (Salathé et al. 2014). The

Peak flow on the Skagit River near Mount Vernon, Washington by day of year for a contemporary and two future periods based on dynamical downscaling of one global climate simulation (Salathé et al. 2014).

results of this coupled simulation suggest an increase in flood risk during the 21st century. Other work used the Parallel Climate Model GCM to drive the MM5 atmospheric and CMAQ air quality models to project changes of ozone and particulates (PM2.5) over the U.S. through the mid-20th century (Avise et. al., 2009). WRF has also been linked to a regional ocean model to project future changes in Puget Sound and coastal estuaries (Moore et al, 2015). The results of these studies and others are valuable but incomplete, since they are driven by only one global climate model simulation.

A regional effort is currently underway to understand the biogeochemical implications of global climate for the Northwest. Known as BioEarth, this effort will make use of a variety of regional models to understand

BioEarth Model Linkage Schematic

future changes in agriculture, surface processes, and hydrology over the Columbia River Basin (Adam et al. 2013; Liu et al 2014). BioEarth could make substantial use of the diversity of regional simulations made possible by the proposed consortium effort.

In another regional effort, the Platform for Regional Integrated Modeling and Analysis (PRIMA) has been developed by PNNL researchers to represent key natural and human systems to support regional-scale decision making (Kraucunas et al. 2014). PRIMA integrates models of regional climate (WRF), land surface (CLM), river transport and stream temperature (MOSART), water management (WM), agriculture and land systems (EPIC, AgLU, LULCC), electricity demand, operations, and expansion/siting (BEND, EOM, CERF), and socio-economics/integrated assessment (GCAM). The coupled WRF-CLM model of PRIMA has been used to downscale global climate simulations from 1975 – 2100 to the conterminous U.S. at 20 km resolution (Gao et al. 2014), with hourly model outputs used to drive other PRIMA models to assess water scarcity (Mohamad et al. 2015), evaluate feasibility of power plant expansion constrained by land and water availability (Rice et al. 2015), among other applications

The value of dynamically downscaled regional models can be enhanced substantially by statistical post-processing, which can include the removal of systematic biases, the weighting of models by their ability to duplicate contemporary climate, and the combination of many model runs to produce probabilistic forecasts of the future state of the regional climate. The UW group has substantial experience in bias correction of dynamically downscaled climate simulations (e.g., Salathe et al. 2014) and sophisticated Bayesian Model Averaging (BMA) post-processing of high-resolution ensembles produced by a regional weather forecasting system (Raftery et al. 2008).

Tasks of the Northwest Climate Modeling Consortium

The Northwest Climate Modeling Consortium will support the creation of actionable, state-of-the-science projections of the implications of climate change for the northwest U.S. The key technology will be the dynamical downscaling of global climate models using high-resolution regional atmospheric, hydrologic, oceanic and air quality models as well as sophisticated statistical post-processing.

An important aspect of the proposed effort is the use of large numbers of global climate model simulations to ensure that the uncertainties in the regional projections are defined and evaluated.   Of great significance and value are regional climate signals that are shared by many models and simulations. We currently have access to output from roughly two-dozen global climate models as part of the CMIP-5 effort (Coupled Model Intercomparison Project, Phase V) of the IPCC. Removing global climate models that fail to simulate realistically the meteorology of the region is essential. Thus, he first task will be to examine available runs and determine the subset that most realistically simulates the contemporary climate of the eastern Pacific and western North America.   This subset of skillful global climate model simulations over the contemporary period will then be used for dynamical downscaling.   Based on initial evaluations of the CMIP-5 runs, we estimate that roughly 10-15 global models provide sufficiently realistic simulations of the large-scale circulations and their interannual to decadal variations that influence the regional climate of the western U.S. It is also possible to secure additional simulations collected/run by other groups (e.g., NCAR) or to run additional global model runs ourselves.

These global model simulations will be downscaled over the western U.S.   We expect to use the Weather Research and Forecasting (WRF) system as our primary atmospheric model using a 12-km grid spacing over the region, but it is certainly possible to use others. As shown by previous research, 12-km grid spacing provides sufficient resolution to realistically simulate the influence of regional terrain and land-water contrasts. Earlier studies revealed that it is important to have a far larger intermediate resolution domain that covers the entire Rocky
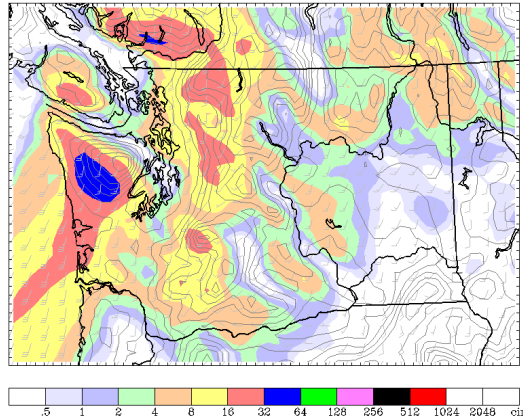
WRF model simulations with 12-km grid spacing are capable of predicting key regional scale features such as heavy precipitation on the windward side of the Olympics and rain shadowing on the northeast side.

Mountains, otherwise the unrealistic low terrain of the global climate models allows cold air to flood westward over the West Coast. We propose to use a 36-km domain for this role. Finally, there will be an outer 108-km resolution domain that will serve as the interface between the regional and global modeling systems. This outer domain will be nudged to evolve similarly to the global model, which has comparable resolution. Such nudging reduces boundary problems and lessens regional model drift. Testing of various nesting configurations will be an important part of the initial stage of this effort. One-way nesting will be used on the boundaries and bias correction of sea surface temperatures (SST) will be explored.
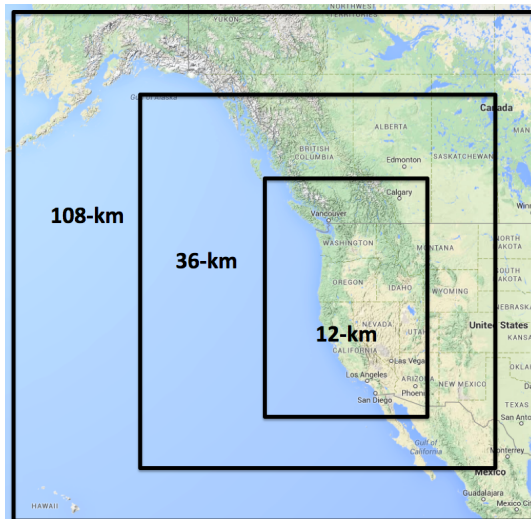
Potential regional climate model domains.

We will also evaluate currently available physical parameterizations (e.g., Land Surface Models, boundary layer schemes, radiation schemes) over an extended contemporary period to determine which combination produces the most skillful downscaled simulations and best duplicate contemporary climate statistics. The evaluation and long-term testing of the Northwest Modeling Consortium using the same (WRF) atmospheric modeling system will provide substantial guidance regarding the optimal physics for the region.

Each downscaled simulation will encompass the 120-year period from 1980 to 2100. Initially, at least one high-resolution run will be done for each global model but, given sufficient computer resources, additional simulations will be carried out to better define model uncertainties and to support specific user needs. For example, uncertainties due to model physics can be examined by using different physics parameterizations or stochastic physics available in the WRF model.   It is also possible that regional climate models others than WRF can be used The regional effort could also drive additional simulations using other global model simulations that are currently available (such as CCSM as described in Deser et. al,. 2012). The regional climate simulations will include atmospheric, land surface, ocean, air quality and hydrologic simulations driven by WRF.

Post-processing of the regional model output is an essential step. All models have systematic biases, and there is inevitably a lack of spread using the limited number of global model simulations that are available (Liu et al., 2013).   Possible post-processing steps include bias-correction, the removal of known systematic biases in the model system; weighting the simulations as a function of the fidelity of each model to observations during the contemporary period; and creating probabilities based on the variability of the climate models in time. Bayesian Model Averaging (BMA) is a particularly promising candidate. The use of post-processing of regional climate simulations have been shown to improve the fidelity of the projections (Salathe et al., 2014) and similar post-processing enhances the skill of regional ensembles used in weather prediction (Raftery et al., 2008)

Although the initial work of this project could be completed in 2-3 years with sufficient support, the proposed effort would ideally be an ongoing project, with continuous improvement of the regional projections as the science/technology inevitably improves. Furthermore, the adaption and application of the regional model predictions to stakeholder/member needs will evolve and grow in time.

The results from these simulations will be made available to the supporting consortium members through both gridded output files and graphical summaries. Output data will also be available for further analysis by the research UW Climate Impacts Group, the USDA Climate Change Resource Center and the Oregon Climate Change Research Institute (OCCRI) as well as other groups identified by consortium members.

A Regional Cooperative Entity

The regional climate modeling effort would include modeling groups at the University of Washington, Washington State, PNNL, and Oregon State as well as dedicated climate impacts groups in Washington and Oregon. Project scientists will work with consortium members to (a) develop a research agenda that addresses their goals and (b) facilitate the use regional model projections for use in decision-making. Over time, it is possible that stakeholders in California will join the consortium.

Research, model development, and model simulations will be completed under the auspices of a multi-institution effort that will be created with consortium support. The University of Washington will lead the atmospheric, hydrologic and ocean simulations, while Washington State University will play a central role in the use of the downscaled runs for air quality, wildfire,

agriculture and smoke-related issues. The Pacific Northwest National Laboratory also brings to bear considerable experience in regional climate modeling, particularly regarding the impacts of aerosols and implications for regional drought. The Oregon Climate Change Research Institute (OCCRI) has explored the use of personal computers for running intermediate-resolution (25-km) climate simulations over a limited domain, and these runs will be evaluated along with the higher resolution climate simulations created under this effort. The Northwest possesses a substantial base of experience and knowledge in regional climate modeling and application; the cooperation and joint efforts of these groups will foster rapid progress.

Organizational Structure and Governance

The consortium will be managed by an oversight board limited to supporting consortium members. The minimum annual contribution for voting membership will be decided by a majority decision of supporting consortium members. The consortium will elect a chairperson out of its ranks who will organize and chair meetings, which will take place three to four times a year.

Computer Resources

The regional climate simulations undertaken for this project will require substantial computer resources for the extended simulations. Completing a century-long atmospheric simulation at sufficient resolution to simulate realistic weather/climate features within a "wall-clock" time of roughly a month requires approximately four nodes (with 20 processors each) using the latest Intel (Haswell) processors. Since we anticipate running several regional climate simulations simultaneously (in order to sample the range of projections), we estimate that 16 nodes will be required for the new center. In addition, these runs will produce huge volumes of output; one possible solution is the purchase of a large RAID disk server (100 terabytes). The estimated cost of the required hardware is approximately $120K based on current prices. In addition, there would be modest annual costs for technical support for the acquired cluster (approximately $10K per year). Addition computer resources will be required for the ocean, hydrological, and air chemistry components of the project, although it is possible they could be run for shorter periods to reduce the computer requirements. The necessary resources can be acquired by purchasing a cluster or by purchasing part of a preexisting system such as the UW Hyak cluster. Another possibility is to purchase access to commercial resources, such as those provided by Amazon, Google, or a range of private-sector vendors. . It also may be possible secure computer resources from a national supercomputer center, such as those run by the Department of Energy, NASA, NOAA or NSF.

Personnel

Initial staffing requirements are (1) a portion of an FTE for the principal scientist of the effort, who will direct the research and interact with the consortium; (2) a full-time research scientist to oversee the model simulations and to carry out the post-processing/analyses required to create useful products; and (3) approximately one FTE for a support scientist to perform computer simulations, manage data and, do other ancillary tasks. More detailed analyses of results and

development of additional applications will require additional staff scientists. We expect that the center will grow to support at least another one to two research or application scientists.

Support of the Northwest Climate Modeling Consortium

Support for the WRCMC can be divided into initial costs and ongoing expenses. The initial cost, primarily for computers and data storage hardware is approximately $120K. We estimate ongoing expenses of about $200K to $250K a year for the initial scientific staffing. Support for these expenses will come from the contributing members of the consortium, and could take on a variety of forms, such as operational funding and targeted research grants. Supporting members will direct the work completed under this project, ensure that simulations are designed to address their information needs, and will have access to model output and analyzed products for their own use. Furthermore, WRCMC staff will be available for consultation and assistance in creating a limited array of products tailored to the specific needs of the consortium members. It is hoped that the UW College of the Environment will be able to provide space to house consortium personnel.

Summary Remarks

Society today has a pressing need to understand the regional implications of global climate change. In many ways, this is one the greatest scientific and practical problems of our time since it influences important decisions related to natural resources, adaptation, and environmental vulnerability. Dynamical downscaling of global climate model output is the most rigorous approach to providing decision-relevant local-scale information. Although the basic technology exists to complete such downscaling, and the region is rich in the necessary expertise, the coordinated effort necessary for developing critically needed regional predictions requires a broader base of support than has been assembled to-date. Furthermore, there are gaps in the science/technology that require addressing for further progress.

The proposed effort will facilitate the rapid development of actionable regional climate predictions by creating a regional climate-modeling consortium that will enable and support the necessary simulations and associated analysis. By each contributing a modest amount of support, the members of the consortium will secure access to a set of regional model simulations and associated products that they cannot afford to acquire individually. In addition, consortium members will work in close coordination with faculty and research scientists at the University of Washington, Washington State University, and other participating institutions in leading edge regional climate model research and development. As demonstrated by existing consortia created to fill regional needs for improved weather prediction, long-term collaborations between a highly interested user community and a dedicated research effort can produce extraordinarily useful environmental guidance and benefit to all.

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Appendix: Previous Related Projects Based on Regional Dynamical Downscaling of Global Climate Simulations

Estimates of 21st Century Flood Risk in the Pacific Northwest Based on Regional Scale Climate Model Simulations (Funding agency: USACE; PI: Eric Salathé, UW). Initial estimates of changing flood risk in the Columbia Basin using statistically downscaled scenarios based on monthly GCM data are very conservative and do not project potential changes in precipitation extremes at daily time scales. However, studies using Regional Climate Models (RCMs) have shown robust increases in precipitation intensity, particularly on the west slopes of the Cascades, suggesting increased flood impacts in these areas. To further evaluate these potential changes, this project has downscaled daily precipitation, temperature, and wind simulations from the Weather Research and Forecasting (WRF) RCM implemented at 12 km resolution to drive a physically based hydrologic model (the Variable Infiltration Capacity (VIC) model at 1/16th degree resolution). Results show substantially different future flood risk characteristics in many basins around the region.

Modeling favorable habitat areas for Alexandrium catenella in Puget Sound and evaluating the effects of climate change (Funding agency: NOAA ECOHAB; PI: Stephanie Moore NOAA/NMFSC; UW lead: Eric Salathé). This project is a collaboration between scientists at NOAA NWFSC and the UW to identify the environmental and climatic conditions favorable to *Alexandrium catenella* cyst germination and vegetative growth. The objectives are both near-term seasonal forecasts of toxic blooms and the evaluation of climate change impacts. Regional climate modeling activities include linked simulations of the Weather Research and Forecasting (WRF) model the Variable Infiltration Capacity (VIC) model and the Regional Ocean Modeling System (ROMS). Simulations of historic, current, and future climatic conditions will be used to understand climatic influences on *Alexandrium catenella* in Puget Sound. In particular, we will model the effects of freshwater inputs, coastal upwelling, exchange through the Strait of Juan de Fuca, and direct energy and water fluxes on water properties in Puget Sound.

Ensemble Analyses of the Impact and Uncertainties of Global Change on Regional Air Quality in the U.S. (Funding agency: EPA/STAR; PI: Brian Lamb (WSU); UW lead: Eric Salathé). A collaboration among university and federal researchers at WSU, UW, US Forest Service, NCAR, and Colorado State to answer questions related to the effects of global change on regional air quality. Specific outcomes are: 1) Quantitative estimates of uncertainties as part of the answers to our research questions. 2) Presentation of results in terms appropriate for air quality regulatory needs. 3) Assessment of the relative importance of the effects of local US emission changes, climate change, land use change, and increasing Asian emissions upon future air quality in the continental US. 4) Development and application of a relative reduction factor (RRF) approach similar to that use for SIP model analyses modified to include a climate impact factor. 5) analysis of Policy Relevant Background simulations for the US. 6) analysis and projection of modeling uncertainties through a limited ensemble analysis approach.

Regional-Scale Earth System Modeling: BioEarth (Lead: Jennifer Adam WSU; Funding: USDA; 2011-2016). A larger team of faculty across many institutions but led by WSU is currently developing a regional-scale Earth system model *that* incorporates dynamic vegetation and biogeochemical cycling in managed and unmanaged landscapes, as well as atmospheric, aquatic, and economic processes. The goal of BioEarth is to better understand the implications of natural

(land and water) resources management strategies on Earth system processes and linkages at finer temporal and spatial scales than are currently possible with global-scale models.