Time of Emergence of Climate Change Signals in the Puget Sound Basin

Project Report

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Executive Summary

The Time of Emergence analysis and prototype online tool were designed to help users explore the basic question: when and where could climate change matter across the Pacific Northwest? This is a new approach to delivery of climate change information that (1) focuses on identifying the time when climate change causes local conditions to deviate significantly from the past, which we call the *Time of Emergence* of climate change and (2) provides this information in the context of a wide range of scientifically credible future potential conditions, in order to stimulate and support user understanding of the implications of scientific uncertainty for decisions and priority setting.

Because natural and human systems tend to be somewhat adapted to historical climate fluctuations, ecological and societal disruptions may occur when climate change causes local conditions to deviate significantly from the past. A key input to deciding and prioritizing actions on climate change, therefore, is information about when and where the distinctive trend due to climate change is projected to emerge from the noise of natural climate variability. Although this information can be gleaned from existing climate change scenarios, it has not been explicitly characterized for variables and spatial scales relevant to local decision-making. Further, most climate change projections are reported without contextual information about the significance of projected changes relative to variability in past conditions. The plethora of existing local climate change projections, based on different emission scenarios, global climate models and downscaling methods, increases the difficulty of identifying when and where the effects of climate change could matter. As a result, despite the wealth of downscaled climate change projections for the PNW, potential users of this information still struggle with interpreting multiple scenarios, finding information about projected changes in environmental conditions of relevance to their particular management concerns, or simply the technical challenges of extracting relevant information from the massive datasets available from climate data providers.

The Time of Emergence project enables a new look at future climate change from the point of view of when and where changes could matter compared to both typical variability in conditions and management sensitivity to those fluctuations. We combined climate statistics, engagement with policy and management entities, and online data delivery platform development, to develop a new approach to climate change decision support based on the concept of “Time of Emergence” for detectable change in management-relevant measures of the climate and environment for the US Puget Sound.
basin and Pacific Northwest (PNW). Variables for computation were selected in consultation with federal, state, and local decision-makers, who identified dozens of temperature-, precipitation-, hydrologic- and streamflow-related variables relevant to local management and operations, including proxies related to drought, energy, fish, floods, human health, infrastructure, streamflow, and water quality. ToE was computed for 35 types of variables (158 specific variables) using the “signal-threshold” method (Mauran 2013) and existing global, statistically- and dynamically-downscaled climate model outputs from Coupled Model Intercomparison Project phases 5 and 3 (CMIP5 and CMIP3) and existing simulations of regional hydrological change using the Variable Infiltration Capacity model. Analyses were performed at the resolution of the input datasets (i.e., 1/8- and 1/16-degree for gridded data; discrete river gauge stations for streamflow projections) and, for the gridded data, results were spatially aggregated for WA, OR and ID counties and for 4th-level (8-digit) hydrological unit codes (HUCs) in the PNW region.

In addition to databases of Time of Emergence results, intermediary computational outputs, and a library of maps for visualization of spatial variability in signal emergence, a final product is a prototype open online system designed to support evaluations of relative climate risks and efforts to prioritize preparatory action. The prototype tool enables users to visualize and compare the Time of Emergence of significant change for different variables and PNW locations and to explore the sensitivity of results to reasonable alternative choices about potential future conditions and management sensitivity. Users can explore the sensitivity of projected Time of Emergence to (1) user tolerance for change (low and high management sensitivity to climate fluctuations, triggered by the 5% high/5% low and 20% high/20% low most extreme historical conditions, respectively), (2) climate modeling uncertainty (represented by high and low emission scenarios; an ensemble of up to 21 global climate models, depending on input dataset; and statistically- and dynamically-downscaled regional projections), and (3) uncertainty in estimating the climate change trend. The prototype online tool is designed to provide scientific and technical information about the underlying methods, assumptions, datasets, and appropriate interpretation and application of results, as well as tutorials of how a user might use the tool to support climate change decision-making. The tool supports user extraction and downloading of visualization products and underlying data.

The online tool is implemented in Drupal using the standard Drupal Content Management System, with custom modules to provide advanced filtering, user query, and dynamic visualization capabilities. The underlying database engine is MySQL, a standard open source database that powers both the underlying database for the Drupal site and a separate database that manages and serves the climate data. Designed as a prototype, the system can be expanded in the future to deliver additional Time of Emergence results (for
different variables, input datasets, and/or user-selected analytical parameters), enhanced visualizations, or other features desired to enhance the user experience.

In the Time of Emergence project, we have reduced the burden for regional practitioners to access and interpret climate change projections by (1) downloading and formatting downscaled model output, (2) using these projections to compute locally-specific, management-relevant variables, (3) evaluating the Time of Emergence for these variables under a range of plausible assumptions about future climate and management sensitivity to change, (4) developing syntheses of these results to indicate agreement across numerous global climate models, and for particular locations and levels of agreement, (5) producing a library of maps indicating spatial variability in both Time of Emergence and model agreement, and (6) developing a prototype online tool for exploring and accessing these results, in order to provide both novice and sophisticated users relatively easy entry into these complex and numerous datasets. By accurately representing the variability and uncertainty in projecting future climate, the prototype online tool enables user selection of the scenarios best fitting their decision context and risk tolerance. Combined with information about relevant response times, these results can be used to identify priority areas for more detailed analysis to support climate risk reduction. The flexible method of analysis, visualization and data delivery can be efficiently applied to new data sets as they emerge or are updated.
1 Introduction

Throughout the Puget Sound and US Pacific Northwest, government entities at all levels, communities and businesses are preparing for the effects of climate change. Some are just beginning to evaluate the potential implications of a changing climate for their assets and objectives; others are incorporating climate change projections into regulatory decision making, infrastructure investments and long-range planning. Across the region, similar questions arise. Regulators and resource managers, planners and policymakers faced with an array of competing tasks and priorities and wondering whether climate change adaptation is an issue for today or can be put off until tomorrow ask, “When will changes be big enough to matter?” Those wondering where to prioritize their efforts between different programs and management objectives ask, “Which conditions are likely to change first because of climate change?”, while those considering where to prioritize climate change responses across the region ask, “Where are conditions likely to change first because of climate change?” Given the plethora of existing projections for changes in regional climate, many further inquire, “What level of certainty can be ascribed to any answer to these questions?”

Because natural and human systems tend to be somewhat adapted to historical climate fluctuations, it is when climate change causes local conditions to deviate significantly from the past that ecological and societal disruptions may occur. A key input to deciding and prioritizing actions on climate change, therefore, is information about when and where the distinctive trend due to climate change is projected to emerge from the noise of natural climate variability. This type of information can be combined with information about local sensitivities, design standards or critical thresholds to help identify the relative need and priority for climate change adaptation activities.
Although information about the “Time of Emergence” for detectable change in management-relevant measures of the climate and environment can be gleaned from existing climate change scenarios, it has not been explicitly characterized for variables and spatial scales relevant to local decision-making. Multiple local climate change projections, based on different emission scenarios, global climate models and downscaling methods, increase the difficulty of identifying when and where the effects of climate change could matter. For many potential users, furthermore, useful climate change information is often hard to find, difficult to digest and compare, and rarely provided at spatial and temporal scales relevant to management.

Evaluating when and where climate change could matter requires information about the expected rate and plausible range of projected climate change – for specific locations and management-relevant environmental conditions, and knowledge of management sensitivity to change for specific systems and objectives. This effort combines climate statistics, engagement with policy and management entities, and data delivery platform development to develop a new approach to climate change decision support based on the concept of “Time of Emergence” for detectable change in management-relevant measures of the climate and environment for the US Puget Sound basin and Pacific Northwest (PNW), with goals of:

- Consolidating disparate sources of climate change information
- Developing a flexible method of analysis, visualization and data delivery that can be efficiently applied to new data sets as they emerge or are updated
- Providing a variety of future scenarios in order to illustrate to the user community the existing range of uncertainty in projections of future climate
- Providing a tool useful for novice and sophisticated users – from those seeking general insights on how and where significant climate change could occur and wondering why there is a range of climate change projections, to those looking for a tool to support initial identification (or screening) of priority locations or issue areas in which to focus climate change risk reduction activities
- Raising awareness about complexities, uncertainties and limitations associated with projections of future climate
This report describes the *Methods* (Section 2) used to compute Time of Emergence for locally-specific, decision-relevant variables in the Puget Sound and Pacific Northwest (PNW) regions, including input datasets, selection of variables and locations for Time of Emergence analysis, analytical methods, and post-processing. It describes the *Web Delivery* (Section 3) of these results, including the user interface, navigation, selection options, and accompanying supporting information for exploring the variation of Time of Emergence results by location within the region, by variable, and as a result of different choices for parameters including emissions scenario, management sensitivity to change, estimated rate of climate change, and input dataset. Our *Strategy for Incorporating Uncertainty in Computing and Communicating Time of Emergence* is described in Section 4. Section 5, *Website Architecture*, describes the technical specifications of the prototype website, including its structure and framework, data engine, and user capabilities of data extraction and download. *Project Outputs and Data Archival* are described in Sections 6 and 7, respectively, while Section 8, *Moving Forward*, describes potential avenues of improvement or expansion of the prototype web tool.
2 Analytical Methods

2.1 Time of Emergence

In its simplest form, Time of Emergence (ToE) is a way of expressing the rate of climate change over time as compared to the range of past variability. The climate change signal is said to “emerge” when it becomes large compared to variability. Thus, three values need to be considered in computing the ToE of a variable: 1) the rate of change in the variable due to climate change 2) the range of past variability in the variable and 3) the threshold at which the change becomes large compared to variability. While there are well-established methods to compute each of these, they raise a number of issues that can substantially affect the results. Below we discuss how we selected the most appropriate method and how this choice affects the results of the study.

The ToE analysis is applied to management-relevant climate variables, which are described in the following section. These variables include values, such as the annual frequency of days with precipitation exceeding the historic 95% percentile, which must be computed from climate projection data of basic climate variables such as daily maximum/minimum temperature, precipitation, runoff, etc. This project focuses on regional-scale impacts and assessment, and so has used downscaled, daily time-step climate data for all variables. A variety of existing scenarios for future global and regional hydro-climatic conditions were used to compute ToE, including global, statistically- and dynamically-downscaled climate model outputs from Coupled Model Intercomparison Project phases 5 and 3 (CMIP5 and CMIP3) and existing simulations of regional hydrological change using the Variable Infiltration Capacity model. The selection and sources of these input datasets are described below, along with the methods to select and derive the management-variables used in the Time of Emergence analysis (Figure 1).
Figure 1. Flow chart indicating data sources, analytical steps, and outputs for Time of Emergence Analysis.
2.2 Climate Data Sets

2.2.1 Global Models

The Coupled Model Intercomparison Project (CMIP, e.g., Taylor et al. 2012, http://cmip-pcmdi.llnl.gov/cmip5/) has organized international global climate model centers to support the Intergovernmental Panel on Climate Change (IPCC) assessments with simulations of the past and future climate. The CMIP provides a standard experimental protocol for coupled atmosphere-ocean general circulation model simulations, and we use global model simulations exclusively from CMIP experiments. There are two generations of the Coupled Model Intercomparison Project currently in use, CMIP3 (used in the IPCC Fourth Assessment Report (AR4)) and CMIP5 (IPCC AR5) (there was no CMIP4). The global models have been extensively studied and compared to observations over the PNW region for CMIP3 (Mote and Salathé, 2010) and CMIP5 (Rupp et al, 2014) simulations. Given this thorough documentation of model performance and the published guidance that choosing a large model ensemble is more reliable than attempting to select only a few top models (Mote and Salathé, 2010), we have opted to perform the ToE analysis for all global model results available for the PNW (after appropriate downscaling or hydrologic simulations; see below). The final data delivery products allow users to visualize the contributions of individual models to the ensemble results.

Because downscaled scenarios and derived hydrologic products from CMIP5 are only now becoming available and because there has been no conclusive evaluation of relative quality of CMIP5 and CMIP3 for the PNW, we used results based on both CMIP3 and CMIP5 global model simulations as described below. Where resources limited the delivery of results (via the prototype online tool described below), we prioritized results based on the CMIP5 global simulations, where available, in recognition of the strong interest from the stakeholder community in focusing on the more recent simulations.

For both CMIP3 and CMIP5, we have selected a “High” (RCP8.5 and SRES A1B) and “Low” (RCP4.5 and SRES B1) emissions scenario (RCP4.5 and RCP8.5 for CMIP5, Van Vuuren et al. (2011), SRES B1 and A1B for CMIP3, Nakicenovic and Swart (2000). The
“High” scenario is based on rapid greenhouse gas emissions with little to no mitigation strategies and a “business as usual” approach to energy usage, which implies an earlier ToE estimate due to greater effects of climate change; “Low” is based on lower emissions, a high level of mitigation strategies for RCP 4.5, and use of alternative energies, and implies a later ToE estimate. The two sets of emissions scenarios (RCP and SRES scenarios) are noted for the user since ToE results are provided from a suite of different underlying climate data sets derived from CMIP5 and CMIP3, respectively.

As noted in previous paragraphs, CMIP3 predates CMIP5, and there are some notable differences between the two datasets. The key difference is mainly in the emission scenarios. The SRES scenarios used in CMIP3 used a sequential approach or "storyline" based on emission and socioeconomic scenarios and their respective radiative forcing. The Radiative Concentration Pathway (RCP) scenarios used in CMIP5 used a parallel approach with concentrations of greenhouse gases, aerosols, and other gases evolving based on a range of future radiative forcings and mitigation techniques. The SRES did not incorporate any mitigation policies in their storyline. Another key difference between the two datasets is that the CMIP5 models have finer spatial and vertical resolution, with some models incorporating the carbon cycle and atmospheric chemistry. For more detailed comparisons of CMIP3 and CMIP5, see Taylor et al. (2012), Andrews et al. (2012), Knutti et al. (2013) (global) and Mote et al. (2013) and Snover et al. (2013) (PNW).

2.2.2 Downscaling and Hydrologic Modeling

The majority of data used for the ToE analysis were derived from downscaled global climate model simulations using the Bias-Corrected Statistical Downscaling (BCSD) approach (Tohver et al. 2014; Reclamation 2013) for both CMIP3 and CMIP5 scenarios. This downscaling method and data products are well established (Hamlet et al 2013), and the downscaled CMIP3 data have been widely used in climate impacts studies (Tohver et al. 2014). The BCSD results provide daily Tmin, Tmax, and precipitation data on a high-resolution latitude-longitude grid over the region. For this project, we have used downscaled climate data for the simulated time period 1950-2100 (for both datasets, the
data do not begin until 1950). This period includes fifty years of 20th century climate to establish the historic climate variability and then extends through the 21st century to project the climate change signal.

The downscaled scenarios have previously been used as input for hydrologic simulations using the Variable Infiltration Capacity (VIC) hydrologic model (Reclamation 2013). The VIC model is well established, and simulation output has been widely used in climate impacts studies (e.g., Tohver et al, 2014; Salathé et al 2014). The VIC simulations provide spatially distributed hydrologic variables on the fine-scale latitude-longitude grid as well as streamflow volumes routed to specific river locations. The management-relevant climate variables that were analyzed for Time of Emergence (described below) were computed from these downscaled and hydrologic data.

The primary BCSD data set is based on the CMIP5 global climate model project and obtained from the “Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections” project (Maurer et al. 2007; Reclamation 2013; gdo-dcp.ucllnl.org/downscaled_cmip_projections) in which downscaling was performed to a 0.125° latitude-longitude grid (~12km by ~12km). For this effort, we selected a subset of 21 (from ~37 potential) global climate system models from this dataset based on the following criteria: coupled models using standard component models, i.e., component models that have subsequent versions and have been well documented in the metadata and literature (rather than, e.g., CHEM or perturbed physics component models); choice of a single model implementation rather than multiple versions of models from specific modeling centers; models for which simulations were available using both RCP4.5 and RCP8.5; and models for which VIC simulations were available using the downscaled projections as input. We refer to this set of statistically downscaled projections from CMIP5 as “BCSD5.”

Although VIC model simulations using CMIP5 models have been completed, and routed streamflow output is available (Reclamation 2013) and was used in this analysis, no gridded hydrologic variables (such as soil moisture or snow water equivalent) have been
made available from this dataset. Consequently, we also incorporated both downscaled climate variables and VIC hydrologic simulations from earlier BCSD downscaling of seven CMIP3 global models to a 0.0625° grid (~6km by ~6km) (Hamlet et al. 2013, Tohver et al. 2014, http://warm.atmos.washington.edu/2860/). All of the available CMIP3 climate models from this dataset (total of seven) were used in this analysis; we refer to this set as “BCSD3.” We note that for the temperature, precipitation, and hydrologic variables VIC results were available from only six of the seven CMIP3 models. The complete list of BCSD5 and BCSD3 models used in this effort is provided in Table 1.

The BCSD5 and BCSD3 downscaled global climate model simulations used in this analysis could be termed ‘ensembles of opportunity’ since the ensemble members have not been specifically designed to span the full range of uncertainty. There is no weighting or bias correction; each model is assumed to be independent of the others in the ensemble. An ‘ensemble of opportunity’ is comprised of models with generally similar structures (forcings, spatial resolution (e.g., truncation level in spectral space), etc.) because they were usually developed at the same time for the same reasons (i.e., IPCC reports). However they will likely have different parameter choices and calibration histories (Stephenson et al. 2012).

Table 1. List of climate models and their organizational affiliations used in this analysis.

<table>
<thead>
<tr>
<th>Model</th>
<th>Organization</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCESS1-0</td>
<td>Commonwealth Scientific and Industrial Research Organization/ Bureau of Meteorology, Australia</td>
<td>CMIP5</td>
</tr>
<tr>
<td>BCC-CSM-1-1</td>
<td>Beijing Climate Center, China Meteorological Administration, China</td>
<td>CMIP5</td>
</tr>
<tr>
<td>BNU-ESM</td>
<td>Beijing Normal University, China</td>
<td>CMIP5</td>
</tr>
<tr>
<td>CANESM1</td>
<td>Canadian Centre for Climate Modelling and Analysis, Canada</td>
<td>CMIP5</td>
</tr>
<tr>
<td>CCSM4</td>
<td>National Center for Atmospheric Research, University Corporation for Atmospheric Research, USA</td>
<td>CMIP5</td>
</tr>
<tr>
<td>CESM1-BGC</td>
<td>National Center for Atmospheric Research, University Corporation for Atmospheric Research, USA</td>
<td>CMIP5</td>
</tr>
<tr>
<td>CMCC-CM</td>
<td>Euro-Mediterranean Center on Climate Change, Italy</td>
<td>CMIP5</td>
</tr>
<tr>
<td>CNRM-CM5</td>
<td>National Centre for Meteorological Research, France</td>
<td>CMIP5</td>
</tr>
<tr>
<td>CSIRO-MK3-6-0</td>
<td>Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Center of Excellence, Australia</td>
<td>CMIP5</td>
</tr>
<tr>
<td>FGOALS-G2</td>
<td>Laboratory of Numerical Modelling for Atmospheric</td>
<td>CMIP5</td>
</tr>
</tbody>
</table>
Finally, for comparison purposes, we have also included results from a single regional climate model simulation using the Weather Research and Forecast (WRF) mesoscale model forced by an ECHAM5 global model simulation from the CMIP3 project (Salathé

1 For scenario A1B only for temperature, precipitation and hydrologic variables.
2 For scenario B1 only for temperature, precipitation and hydrologic simulations.
et al 2014). The WRF output has been spatially downscaled to the same 0.0625-degree grid as the BCSD3 dataset and used for VIC simulations to provide hydrologic data. The WRF model gives different results from statistical downscaling in locations where fine-scale feedbacks or terrain effects alter the simulated climate change signal. By design, the BCSD downscaling preserves the magnitude and direction of the climate change signal in temperature and precipitation provided by the global model while removing systematic biases due to unresolved terrain features. WRF explicitly represents high-resolution processes, such as orographic precipitation, mesoscale weather systems, and land-atmosphere feedbacks. These processes can produce localized responses to climate change that are not represented in global models. For example, snow-albedo feedbacks can amplify warming on the margins of the snowpack (Salathé et al 2008) and precipitation trends can differ on windward and lee slopes of terrain (Salathé et al 2010). The simulation used here has been extensively evaluated against observations (Dulière et al 2011) and applied in other climate impacts studies (Salathé et al 2014).

In summary, we have used the following downscaled and hydrologic data:

1. Daily Tmax, Tmin, and precipitation from the CMIP5 BCSD on a 0.125-degree latitude-longitude grid for 21 global climate models (“BCSD5”).
2. Daily Tmax, Tmin, and precipitation from the CMIP3 BCSD on a 0.0625-degree for six global climate models (“BCSD3”).
3. Daily Tmax, Tmin, and precipitation from the CMIP3 ECHAM5 WRF (“ECHAM5-WRF”).
4. Daily spatially-distributed hydrologic variables (e.g. runoff, evapotranspiration) derived from the CMIP3 BCSD on a 0.0625-degree using VIC for six global climate models (“BCSD3”).
5. Daily spatially-distributed hydrologic variables derived from the CMIP3 ECHAM5 WRF using VIC (“ECHAM5-WRF”).
6. Daily streamflow volume at specified river locations derived from the CMIP5 BCSD using VIC for 21 global climate models (“BCSD5”).
7. Daily streamflow volume at specified river locations derived from the CMIP3 BCSD using VIC for seven global climate models (“BCSD3”).
Global climate model simulations downscaled for the PNW using the Multivariate AdaptiveConstructed Analogs (MACA) statistical downscaling method (Abatzoglou and Brown 2012) became available during the course of this project and are perhaps better suited for some specific applications. Nevertheless, due to the preliminary nature of these data and lack of quality assurance, we have not incorporated MACA results in this study.

Because version control issues for data are important to note, the data provenance for all daily data used in this analysis is given below in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Data provenance</th>
<th>Daily Variables</th>
<th>Dataset</th>
<th>Date of Download</th>
<th>Source</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tavg, Tmax, Tmin, Prcp</td>
<td>BCSD5</td>
<td>6-13-2014 through 6-18-2014</td>
<td>ssh: gdo-dcp.ucllnl.org</td>
<td>Thrasher et al. 2013</td>
<td></td>
</tr>
<tr>
<td>Tavg, Tmax, Tmin, Prcp, Baseflow, ET, PET, Runoff, Soil moisture, SWE</td>
<td>ECHAM 5-WRF</td>
<td>11-04-2014</td>
<td>Internal CIG database</td>
<td>Salathé et al. 2010</td>
<td></td>
</tr>
<tr>
<td>Q from Station Data</td>
<td>BCSD5</td>
<td>7-17-2014 through 12-03-2014</td>
<td><a href="http://gdo-dcp.ucllnl.org">http://gdo-dcp.ucllnl.org</a></td>
<td>Thrasher et al. 2013</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Variables and locations for ToE analysis

2.3.1 Calculation

Management-relevant climate variables were computed from the primary climate and hydrologic datasets described above to support the ToE calculations described below.
These climate variables are a time-series of yearly values at each grid cell or river station location for each downscaled global climate model simulation. Depending on the specific climate variable, these may be annual values or variables computed only for days in a specific calendar month or season. These intermediate data have been archived and are available for other applications (see Section 6, Project Outputs).

Approximately 35 types of management relevant climate variables were computed and analyzed for this project as listed in Table 3; many for multiple periods (e.g., months or seasons).

All variables were calculated from daily values. Monthly or annual average variables were calculated from daily data and averaged for a specified time period (e.g., monthly, seasonal, annual, etc.), or the daily min/max determined for a specified season. Frequency variables were calculated based on number of days, or consecutive days, over a percentile or fixed value for the specified time period.

For percentile-based variables, such as “Number of days with 24-hour precipitation exceeding historical 90th percentile, October-March”, the historical period of 1950-1999 (1970-1999 for ECHAM5-WRF, since the WRF simulation time series is only available for the periods 1970-1999 and 2010-2069) was used to construct the reference percentiles. Then a count of the number of days, or of consecutive days, exceeding the threshold was calculated for the full time period. The choice of historical reference period was based on the assumption that management tends to be “generally” adapted to historical climate fluctuations, and that this historical period is relatively long for management related to operations and planning of large infrastructure. See Section 2.4, Computing Time of Emergence, for more information about the choice of historical reference period. Because the appropriate reference period will differ by user and management context, we note the reference period used in online delivery of ToE results (described below) and suggest that future efforts consider providing users the opportunity to explore the implications of choosing different reference periods.
### Table 3. Variables analyzed for Time of Emergence: source and resolution of relevant input datasets.

<table>
<thead>
<tr>
<th>Climate variable [method of calculation]</th>
<th>Data set</th>
<th>Grid spacing or station data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, each calendar month [monthly average of daily average temperature]</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Number of days with daily maximum temperature above 65°F (18.3°C), each calendar month (Mar-Nov)</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Number of days with daily average temperature below 25°F (–3.9°C), winter (Dec-Feb)</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Number of days with daily average temperature above 68°F (20°C), spring (Mar-May) and fall (Sep-Nov)</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Number of days with daily maximum temperature above 90°F (32.2°C), annual</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Number of days with daily maximum temperature at or above 80°F (26.7°C), spring-summer (21 April- 21 August)</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Number of daytime heat waves (3 consecutive days with daily maximum temperature above historical 99th percentile), annual</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Number of nighttime heat waves (3 consecutive days with daily minimum temperature above historical 99th percentile), annual</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Precipitation, each calendar month [monthly average of daily average precipitation]</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Precipitation, fall (Oct-Dec), winter (Jan-Mar), spring (Apr-Jun), and summer (Jul-Sep) [seasonal average of daily precipitation]</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation exceeding historical 90th percentile, October-March</td>
<td>BCSD5, BCSD3, ECHAM5-WRF</td>
<td>1/8-degree (BCSD5) 1/16-degree (BCSD3, WRF)</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation exceeding</td>
<td>BCSD5, BCSD3,</td>
<td>1/8-degree</td>
</tr>
</tbody>
</table>

Page 12-11
<table>
<thead>
<tr>
<th>Description</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical 95th percentile, October-March</td>
<td>ECHAM5-WRF, BCSD3, BCSD5, 1/8-degree BCSD3, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation exceeding historical 99th percentile, October-March</td>
<td>BCSD5, BCSD3, BCSD5, 1/8-degree BCSD3, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation exceeding 2 inches (50.8 mm), annual</td>
<td>BCSD5, BCSD3, BCSD5, 1/8-degree BCSD3, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Maximum 48-hour precipitation accumulation, annual</td>
<td>BCSD5, BCSD3, BCSD5, 1/8-degree BCSD3, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Maximum 24-hour precipitation accumulation, annual</td>
<td>BCSD5, BCSD3, BCSD5, 1/8-degree BCSD3, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation equal to 3 inches (76.2 mm) or more, annual</td>
<td>BCSD5, BCSD3, BCSD5, 1/8-degree BCSD3, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Number of wet sequences (18-day cumulative precipitation exceeding 3.5 inches (88.9 mm)), October-March</td>
<td>BCSD5, BCSD3, BCSD5, 1/8-degree BCSD3, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Runoff, annual [annual average of daily runoff]</td>
<td>BCSD3, BCSD5, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Runoff, each calendar month [monthly average of daily runoff]</td>
<td>BCSD3, BCSD5, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Dryness ratio, each calendar month [fraction of input precipitation lost to evapotranspiration]</td>
<td>BCSD3, BCSD5, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Potential evapotranspiration (PET), each calendar month [calculated by VIC using Penman-Monteith equation where there is assigned natural vegetation and no water limit]</td>
<td>BCSD3, BCSD5, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Actual evapotranspiration (AET), each calendar month [calculated by VIC using calculated sum of evaporation and plant transpiration equation]</td>
<td>BCSD3, BCSD5, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Soil moisture, each calendar month</td>
<td>BCSD3, BCSD5, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Snow water equivalent (SWE), each calendar month</td>
<td>BCSD3, BCSD5, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Coefficient of variation of runoff, annual [annual runoff standard deviation divided by annual mean]</td>
<td>BCSD3, BCSD5, 1/16-degree BCSD5, WRF</td>
</tr>
<tr>
<td>Highest spring runoff date</td>
<td>BCSD3, 1/16-degree BCSD5, WRF</td>
</tr>
</tbody>
</table>
### Variable selection

Identifying a list of candidate variables for Time of Emergence analysis involved consideration of:

- The potential impacts caused by climate change (such as droughts, floods, human health, energy supply, water availability, fish survival) that could have implications for stakeholders’ planning, management, operations or regulatory responsibilities.
- The underlying hydro-climatic drivers of these climate change impacts.
- Stakeholders’ existing or anticipated vulnerabilities, concerns and priorities as climate changes.
- How stakeholders are addressing or plan to address the issues or potential impacts related to climate change.

In addition to informal consultation with U.S. Environmental Protection Agency (USEPA) and U.S. Army Corps of Engineers (USACE), a desktop review of existing literature and available online information was carried out, which included:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Data Source</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streamflow, each calendar month</td>
<td>ECHAM5-WRF</td>
<td>BCSD5, BCSD3</td>
</tr>
<tr>
<td>Streamflow center of timing [number of days from 1st of October at which 50% of the year's flow volume for that water year has passed.]</td>
<td>BCSD5, BCSD3</td>
<td>~100 stations</td>
</tr>
<tr>
<td>Maximum daily streamflow per year</td>
<td>BCSD5, BCSD3</td>
<td>~100 stations</td>
</tr>
<tr>
<td>Maximum daily streamflow, each calendar month</td>
<td>BCSD5, BCSD3</td>
<td>~100 stations</td>
</tr>
<tr>
<td>Minimum daily streamflow, each calendar month</td>
<td>BCSD5, BCSD3</td>
<td>~100 stations</td>
</tr>
<tr>
<td>Number of flood flows per year [number of days per year where flow is more than historical (1950-1999) 90th percentile (high) flow]</td>
<td>BCSD5, BCSD3</td>
<td>~100 stations</td>
</tr>
<tr>
<td>Number of 7-day low flows per year [number of days per year where the consecutive average 7-day flow is less than historical (1950-1999) 10th percentile (low) flow]</td>
<td>BCSD5, BCSD3</td>
<td>~100 stations</td>
</tr>
<tr>
<td>Number of low flows per year [number of days per year where flow is less than historical (1950-1999) 10th percentile (low) flow]</td>
<td>BCSD5, BCSD3</td>
<td>~100 stations</td>
</tr>
<tr>
<td>Lowest mean streamflow for 30 consecutive days per year</td>
<td>BCSD5, BCSD3</td>
<td>~100 stations</td>
</tr>
</tbody>
</table>
• Peer-reviewed publications on the projected changes in climate and the associated impacts across the Pacific Northwest domain (e.g., Bonfilset al. 2008, Markoff and Cullen 2008).

• Information prepared by, and for, specific stakeholders: goals and strategies (e.g., climate action plans such as the 2007 King County Climate Plan and WSU 2011), official and unofficial documents (e.g., technical, annual, research reports, such as Snover et al. 2010, and Hamlet 2011, and presentations), climate change-related studies (e.g., impacts and vulnerability assessments such as Mote et al. 2012 and Turner and Brekke 2011), regulatory standards, guidelines and mandates (e.g., EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards).

These efforts led to the compilation of a candidate list of ~35 hydro-climatic variables (e.g., monthly mean temperature, precipitation and runoff), and proxies for extreme events (e.g., heat waves, droughts, floods) for subsequent Time of Emergence analysis. These variables were considered to be of interest to stakeholders, sensitive to climate change, and ready for analysis on the basis of data availability and accessibility. Subsequent stakeholder consultation through a variety of engagement mechanisms was used to refine the list of variables for analysis.

The initial stage of stakeholder engagement involved developing a brief project description that outlined the motivation and goal of the project, along with the potential for participants to influence outcomes. This project description was circulated via email in December 2013 to 28 regional stakeholders known to be actively engaged in climate change-related issues, and with whom the Climate Impacts Group had an established relationship, to facilitate more rapid response. These included the following entities:

  • Federal agencies: USEPA, USACE, U.S. Department of Interior Bureau of Reclamation (USBR), U.S. Forest Service (USFS)
  • State agencies: Washington State Departments of Health (WADOH), Ecology, Natural Resources, Transportation (WSDOT), Emergency Management Division (EMD), and the Puget Sound Partnership (PSP)
• Local agencies: King County, City of Seattle
• Tribes: Swinomish, Puyallup, Tulalip

Subsequent one-on-one conversations were conducted with seven of the stakeholders via phone and/or in person. These included USEPA and USACE, WADOH, WAEMD, King County, Seattle City Light and tribal entities. These stakeholders were selected because their management domains span the anticipated climate change impacts mentioned above.

The candidate list of 35 hydro-climatic variables was distributed by email to eleven stakeholders in February and March 2014 for comment and feedback. These include USEPA, USACE, USBR, WADOH, Ecology, WSDOT, EMD, PSP, King County, Seattle City Light and the Swinomish, Puyallup, Tulalip tribes. The aforementioned stakeholders were contacted because their activities and operations span the potential range of climate change impacts in the Pacific Northwest region. Additional variables suggested by stakeholders were incorporated to the original list, generating a total of 65 variables.

The final set of variables for analysis (Table 4) were either directly provided in the downscaled climate and hydrology datasets described above or could be derived from these data using techniques established in the literature.

The first step in prioritizing variables for analysis involved eliminating those unsuited to a Time of Emergence analysis due to inadequate data or high uncertainty in the climate projections. For instance, variables related to wind, ocean acidification and sea surface temperature have been excluded from this analysis. Similarly, variables related to wildfire risk have also been excluded due to the complication and high uncertainties in identifying and simulating conditions favorable for fire occurrence. A few variables that were location-specific or relevant to only one or two stakeholders were also given a low priority. Some variables were excluded due to computational infeasibility, given the chosen method for Time of Emergence computation (see section below on “Computing
Time of Emergence”). Computational infeasibility generally relates to variables for which there were little to no historical occurrence (specifically, for which conditions never exceeded the threshold of management sensitivity during the baseline period (1950-1999)) for most of the PNW region. As a result, the threshold for exceedance, and subsequently the ToE, could not be calculated. Requested variables that were excluded from the analysis are listed in Table 5.

**Table 4. Variables analyzed for Time of Emergence, with management relevance and requesting stakeholder(s) identified. “CIG” indicates variables identified for analysis by the Climate Impacts Group, based on the desktop review process described above.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Management Relevance</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, each calendar month</td>
<td>Human Health</td>
<td>CIG</td>
</tr>
<tr>
<td>Number of days with daily maximum temperature above 65°F (18.3°C), monthly March-November</td>
<td>Human Health/Energy Supply</td>
<td>Seattle City Light</td>
</tr>
<tr>
<td>Number of days with daily average temperature below 25°F (–3.9°C), winter (Dec-Feb)</td>
<td>Human Health/Energy Supply</td>
<td>Seattle City Light</td>
</tr>
<tr>
<td>Number of days with daily average temperature above 68°F (20°C), spring (Mar-May) and fall (Sep-Nov)</td>
<td>Human Health/Energy Supply</td>
<td>Seattle City Light</td>
</tr>
<tr>
<td>Number of days with daily maximum temperature above 90°F (32.2°C), annual</td>
<td>Human Health/Energy Supply</td>
<td>Seattle City Light</td>
</tr>
<tr>
<td>Number of days with daily maximum temperature at or above 80°F (26.7°C), spring-summer (21 April- 21 August)</td>
<td>Human Health/Energy Supply</td>
<td>Puget Sound Clean Air Agency</td>
</tr>
<tr>
<td>Number of daytime heat waves (3 consecutive days with daily maximum temperature above historical 99th percentile), annual</td>
<td>Human Health/Energy Supply</td>
<td>Seattle City Light</td>
</tr>
<tr>
<td>Number of nighttime heat waves (3 consecutive days with daily minimum temperature above historical 99th percentile), annual</td>
<td>Human Health/Energy Supply</td>
<td>Seattle City Light</td>
</tr>
<tr>
<td>Precipitation, each calendar month</td>
<td>Water Availability</td>
<td>CIG</td>
</tr>
<tr>
<td>Precipitation, fall (Oct-Dec), winter (Jan-Mar), spring (Apr-Jun), and summer (Jul-Sep)</td>
<td>Water Availability/Flood/Fish</td>
<td>USACE</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation exceeding historical 90th percentile, October-March</td>
<td>Flood/Fish/Landslide</td>
<td>CIG</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation exceeding historical 95th percentile, October-March</td>
<td>Flood/Fish/Landslide</td>
<td>CIG</td>
</tr>
<tr>
<td>Metric</td>
<td>Category</td>
<td>Source</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation exceeding historical 99th percentile, October-March</td>
<td>Flood/ Fish/ Landslide</td>
<td>CIG</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation exceeding 2 inches (50.8 mm), annual</td>
<td>Flood/ Fish/ Landslide</td>
<td>Seattle Public Utilities</td>
</tr>
<tr>
<td>Maximum 48-hour precipitation accumulation, annual</td>
<td>Flood/ Fish/ Landslide</td>
<td>USACE</td>
</tr>
<tr>
<td>Maximum 24-hour precipitation accumulation, annual</td>
<td>Flood/ Fish/ Landslide</td>
<td>USACE</td>
</tr>
<tr>
<td>Number of days with 24-hour precipitation equal to 3 inches (76.2 mm) or more, annual</td>
<td>Flood/ Fish/ Landslide</td>
<td>USACE</td>
</tr>
<tr>
<td>Number of wet sequences (18-day cumulative precipitation exceeding 3.5 inches (88.9 mm)), October-March</td>
<td>Flood/ Fish/ Landslide</td>
<td>City of Seattle</td>
</tr>
<tr>
<td>Runoff, annual</td>
<td>Water Availability</td>
<td>CIG</td>
</tr>
<tr>
<td>Runoff, each calendar month</td>
<td>Water Availability/ Flood/ Fish</td>
<td>CIG</td>
</tr>
<tr>
<td>Dryness Ratio (fraction of input precipitation lost to evapotranspiration), each calendar month</td>
<td>Drought/ Water Availability/ Water Quality</td>
<td>USEPA</td>
</tr>
<tr>
<td>Potential evapotranspiration (PET), each calendar month</td>
<td>Drought/ Water Availability/ Water Quality</td>
<td>USEPA</td>
</tr>
<tr>
<td>Actual evapotranspiration (AET), each calendar month</td>
<td>Drought/ Water Availability/ Water Quality</td>
<td>USEPA</td>
</tr>
<tr>
<td>Soil moisture, each calendar month</td>
<td>Drought/ Landslide</td>
<td>CIG</td>
</tr>
<tr>
<td>Snow water equivalent (SWE), each calendar month</td>
<td>Water Availability</td>
<td>USEPA</td>
</tr>
<tr>
<td>Coefficient of variation of runoff, annual</td>
<td>Water Availability</td>
<td>USACE</td>
</tr>
<tr>
<td>Highest spring runoff date</td>
<td>Flood/ Fish</td>
<td>USEPA / USACE</td>
</tr>
<tr>
<td>Streamflow, each calendar month</td>
<td>Water Availability/ Water Quality</td>
<td>USACE</td>
</tr>
<tr>
<td>Streamflow center of timing</td>
<td>Water Availability</td>
<td>USEPA</td>
</tr>
<tr>
<td>Maximum daily streamflow per year</td>
<td>Flood/ Fish</td>
<td>CIG</td>
</tr>
<tr>
<td>Maximum daily streamflow, each calendar month</td>
<td>Flood/ Fish</td>
<td>CIG</td>
</tr>
<tr>
<td>Number of flood flows per year</td>
<td>Flood/ Fish</td>
<td>USACE</td>
</tr>
<tr>
<td>Number of 7-day low flows per year</td>
<td>Water Availability/ Water Quality/ Fish</td>
<td>King County</td>
</tr>
<tr>
<td>Number of low flows per year</td>
<td>Water Availability/ Water Quality/ Fish</td>
<td>USACE</td>
</tr>
<tr>
<td>Lowest mean streamflow for 30 consecutive days per year</td>
<td>Water Availability/ Water Quality/ Fish</td>
<td>King County</td>
</tr>
</tbody>
</table>
### Table 5. Variables excluded from the analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Source</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of days with daily maximum temperature above 65°F (18.3°C), January, February, December</td>
<td>Seattle City Light</td>
<td>High variance or no historical record of occurrence in Puget Sound / WA</td>
</tr>
<tr>
<td>Number of days with daily maximum temperature below 65°F (18.3°C), each calendar month</td>
<td>Seattle City Light</td>
<td>Every day in historical record fits criteria</td>
</tr>
<tr>
<td>Number of days with daily average temperature above 86°F (30°C), summer (Jun-Aug)</td>
<td>Seattle City Light</td>
<td>High variance or no historical record of occurrence in Puget Sound / WA</td>
</tr>
<tr>
<td>Number of days with daily maximum temperature above 100°F (37.8°C), annual</td>
<td>USEPA</td>
<td>High variance or no historical record of occurrence in Puget Sound / WA</td>
</tr>
<tr>
<td>Number of drought months, annual</td>
<td>USACE</td>
<td>Variable would be 0-12, which is not methodologically suited for this analysis</td>
</tr>
<tr>
<td>Snowmelt Fraction (Fraction of streamflow contributed by snowmelt), each calendar month</td>
<td>USEPA</td>
<td>Variable not directly available in hydrologic model output</td>
</tr>
<tr>
<td>Low Flow Sensitivity</td>
<td>USEPA</td>
<td>Variable not directly available in hydrologic model output</td>
</tr>
<tr>
<td>Annual frequency of 7-day moving avg daily maximum stream temperature above 60°F (16°C), 64.4°F (18°C), 71.6°F (22°C), 75.2°F (24°C)</td>
<td>USEPA</td>
<td>Variable not directly available in hydrologic model output</td>
</tr>
<tr>
<td>Time lag between stream temperature maxima (Tmax_w) &amp; stream flow minima (Qmin)</td>
<td>USEPA</td>
<td>Variable not directly available in hydrologic model output</td>
</tr>
<tr>
<td>[%change in streamflow] / [%change in precipitation], each calendar month</td>
<td>USACE</td>
<td>Requires new cross-walking between routed hydrologic model output (point values) and downscaled precipitation data (gridded)</td>
</tr>
<tr>
<td>Maximum 6-hr wind speed</td>
<td>Seattle City Light</td>
<td>High uncertainty in the projections</td>
</tr>
<tr>
<td>Frequency of days with high (&gt;30 mph or &gt;40 mph) wind</td>
<td>Seattle City Light</td>
<td>High uncertainty in the projections</td>
</tr>
<tr>
<td>Date of first fire</td>
<td>WADOH</td>
<td>High uncertainty associated with projecting fire dates; no timeseries projection of this variable available</td>
</tr>
<tr>
<td>Date of end of fire season</td>
<td>WADOH</td>
<td>Same as above</td>
</tr>
<tr>
<td>Acres burned</td>
<td>WADOH</td>
<td>No timeseries projection of this variable available</td>
</tr>
<tr>
<td>pH at Tatoosh Is. and in Puget Sound</td>
<td>WADOH</td>
<td>No data available</td>
</tr>
<tr>
<td>Sea-surface temperature at Tatoosh Is. and in Puget Sound</td>
<td>WADOH</td>
<td>No data available</td>
</tr>
</tbody>
</table>
2.3.3 Selection of streamflow locations for analysis

Because available resources precluded the analysis of ToE streamflow variables for all available streamflow locations (70 for the BCSD5 dataset; 297 for the BCSD3 dataset), a subset of ~100 locations (~50 from each dataset; Figure 2) was selected for analysis using the following criteria:

1. Locations common to both datasets (i.e., within 5 km)
2. Locations close to (~50 km) the Puget Sound Basin
3. Locations showing diversity in watershed type, for example, rain dominant vs. snow dominant

*Figure 2. Streamflow locations for Time of Emergence analysis of streamflow-related variables listed in Table 8. CMIP3 and CMIP5 indicate source datasets described in the text as BCSD3 and BCSD5, respectively.*
2.4 Computing Time of Emergence

The Time of Emergence for the time series of a climate variable is the point in time when the systematic, long-term change of the variable emerges from historic variability. There are several approaches in the literature for computing ToE, each with advantages and disadvantages for this project. We were guided in our selection to choose an approach that clearly communicated what emergence would imply for managing climate change and that was well-suited to the management-relevant climate variables we analyzed.

There are three approaches in particular that we considered:

1. *Signal to Noise.* From the time series of a climate variable, the time varying climate signal, \( s(t) \), is estimated as the long term monotonic change in the variable. The noise, \( N \), is based on the range of variability (e.g. the standard deviation) over some historic time period. The Time of Emergence is then found at the time \( t \) when \( s(t)/N \) exceeds some value, typically 1 or 2. (See Hawkins and Sutton 2012)

2. *Exceedence Threshold.* The upper limit for the climate variable is set based on some historic reference period. The Time of Emergence is set as the time when a selected number of consecutive years exceed this threshold, for example 3 years, 11 years, or all years. (See Mora 2013)

3. *Signal Threshold.* A climate signal is defined by a linear fit to the time series of the climate variable. The Time of Emergence is set where this line crosses a predefined threshold for emergence. (See Maraun 2013)

We have selected method #3 due to the clarity of communicating the management implications of the emergence threshold and the robustness of the method for a wide variety of climate variables. A key consideration is that for this project, we interpret the Time of Emergence as the time when the change of a variable becomes substantial enough to affect management decisions. In the *Signal Threshold* method, the adjustable parameters and the error interpretation have more obvious connections to management considerations.
The “signal to noise” and “signal threshold” methods (1 and 3) are mathematically similar and through appropriate selections of the adjustable parameters, similar results could be obtained for normally-distributed climate variables. Thus, the primary difference between these methods is in associating the parameters to management considerations. Since many of the stakeholder-relevant variables are extreme values, which are not normally distributed, the signal to noise approach is not appropriate unless it were modified to account for the skewness in the data. The remaining method, “exceedence threshold”, entails some arbitrary choices (e.g., the number of exceedences required for emergence) that make it less robust when comparing ToE across many different models and variables.

In this study, the emergence of a climate variable indicates the time it crosses a threshold value. The thresholds are intended to indicate the boundaries for user tolerance to fluctuations in the variable, and are specified in terms of the historic variability (Figure 3). The thresholds are user-selected to reflect different tolerances for climatic fluctuations, with upper and lower bounds encompassing 60 or 90 percent of the observed variability for 1950-1999. The 60% envelope reflects a narrower tolerance for climatic fluctuations, with a lower bound at 20th and upper bound at the 80th percentiles of historic variability. This narrower envelope can represent a system or management context that could be considered “well” adapted to the central 60% of historical climatic conditions, i.e., a system in which impacts of concern are triggered by the 20th percentile high and/or low historic conditions, and therefore one that is relatively sensitive to climate change. The 90% envelope indicates a wider range of adaptability, with bounds at the 5th and 95th percentiles. This wider envelope represents a system that is relatively insensitive to climate change. For example, consider the variable annual maximum daily precipitation, which has 50 values over the 1950-1999 period. Climate change would be said to cause emergence from the 60% envelope if the mean value for future annual maximum daily precipitation exceeds the 10th greatest historic year or falls below the 10th smallest year. Climate change would cause emergence from the 90% envelope if the mean value exceeds the 3rd greatest historic year or falls below the 3rd smallest year. Exceeding/falling below the upper/lower threshold for the 90% envelope is likely to occur at a later date.
than the 60% envelope. These emergence thresholds (5th, 20th, 80th and 95th percentiles of historical variability) are calculated for each model at each grid cell (for the period 1950-1999 for BCSD5 and BCSD3 and 1970-1999 for ECHAM5-WRF). \(^3\)

The climate signal may be either negative or positive and therefore emerge by crossing out of the envelope at either its upper or lower bound. Consequently, we distinguish between the emergences of a positive or negative trend. For some variables, the different models may not agree on the direction of the trend at a given location, and a single model may give positive or negative trends at different locations or times of the year.

The linear climate signal is calculated for low and high future emission scenarios (RCP4.5 and RCP8.5 for CMIP5, Van Vuuren et al, 2011, or SRES B1 and A1B for CMIP3) using the slope from a least squares regression model. To reflect uncertainty in extracting the climate change signal from a single model realization, we compute the 90% confidence interval in the computed slope. The confidence interval is computed as the standardized error in the slope based on a Student’s t-test. This error term is then added and subtracted from the calculated slope to obtain an upper and lower bound to the climate signal. ToE is then found as the year at which the linear signal crosses the predefined thresholds. All calculations are done at each grid cell of the downscaled data domain. Thus, for each downscaled climate model and each grid cell, we obtain twelve ToE values corresponding to the central, lower, and upper estimate of the climate signal, the two emergence thresholds, and two emissions scenarios.

Three time periods have been selected to represent 1) historic variability (the historical reference period used to define thresholds of emergence; defined as 1950-1999), 2) the climate norm (the value used to represent current climate, and the initial value from which climate change occurs; 1980-2010), 3) future climate trend of the variables

\(^3\) In the prototype online tool described in Section 3, we use the term “Management Sensitivity” to describe these varying levels of user tolerance to projected change represented by the two sets of emergence thresholds. “Low” and “high” management sensitivity to climate fluctuations are triggered by the 5% high/5% low and 20% high/20% low most extreme historical conditions, respectively.
analyzed (defined as when the climate change scenarios are turned on in the global climate model simulations; 2006-2100). The specific time periods were selected in order to accurately represent recent climate, span multiple cycles of natural decadal variability, reflect historic management and infrastructure adaptation to past climate, and conform to climate science community standards. The two historic periods were chosen based on separate discussions and stakeholder considerations and could alternately have been defined to be coincident without any impact on ToE results.
Figure 3. Figurative depiction of computation of Time of Emergence using the Signal Threshold method for a specific variable (in this case, annual number of days warmer than 90 degrees F) at a single grid cell for output derived from a single global model. Top Panel: Time of Emergence is calculated as the year when the climate change signal (the slope from a least-squares regression model of the simulated variable for 2006-2100 added to the climatological baseline for the period 1981-2010) crosses the threshold for emergence (the 5th or 95th percentile of observed variability for 1950-1999). Second Panel: A lower emissions scenario (e.g., RCP4.5 instead of RCP8.5) results in later emergence due to a smaller climate change signal. Third Panel: Lower management tolerance for change (i.e., higher management sensitivity) results in an earlier ToE due to lower thresholds for emergence. Bottom Panel: Uncertainty in the climate change signal, represented by the 90% confidence interval around the slope calculated from the linear regression error term at the 95% significance level, results in earlier or later emergence depending on slope used.

All models will emerge for an arbitrarily high year, even with a near-zero signal, but such high ToE values would not be meaningful. Thus, we flag any model that has not emerged by 2100 for a particular combination of threshold and slope as “non-emergent”.

This method is applied to all climate models in the ensemble, 21 for BCSD5 and 6-7 for BCSD3. To represent the ensemble consensus, we select the median ToE across the ensemble for each grid cell. The median ToE indicates the year at which 50% of the models have emerged. To understand ensemble spread in ToE, for each grid cell we also calculate the year at which 25 and 75% of all models in the ensemble have ‘emerged’. For example, if 16 of the models in the 21-model BCSD5 ensemble have emerged by 2060 at a particular grid cell, the ToE for 75% model agreement is set to 2060 at that grid cell.

We are calculating ToE for a wide variety of climatological variables, and the methodology used in this analysis may not be entirely appropriate to for all variables. An example is in computing the ToE for the time series of the number of days per year when a climate variable exceeds a particular threshold. If this threshold is never exceeded in the historical period, then the emergence threshold is zero, and any occurrence in the future would yield a ToE in the first year, 2001. Nevertheless, without a historical basis for
comparison, there is no ‘noise’ for the variable to ‘emerge’ from, and therefore the concept of emergence, as we have defined it, is not meaningful. One could apply a different concept of “emergence” in these cases, such as using the third occurrence of this event as in Mora (2013). However, these results would not then be comparable. In this case we have flagged the variable as non-emergent; a customized code could be applied in the future for these cases to identify the reason for non-emergence, which may be important for certain users.

Another difficulty occurs for variables where the projected range of variability from a model is very large, so that the sign of the trend in the variable is uncertain. Thus, the lower and upper bounds to the signal (trend) produce emergence of the variable in different directions. For example, we might find a variable that emerges with a positive trend, but where the confidence interval for the computed slope indicates the possibility of an emergence with negative trend. This result generally indicates a high degree of uncertainty in computing the projected climate signal in a given variable and would be reflected in visualizations or other reporting of uncertainty in ToE. For reporting of ToE at different levels of global climate model agreement, if a grid cell showed less than 60% agreement in direction of trend, the median cell value for the ensemble was not calculated and we flag the variable as non-emergent in that grid cell (Table 6).
Table 6. Definitions of “non-emergent” variables used in computing ToE for individual locations and spatially-aggregated results.

Reasons for flagging a variable as “non-emergent” at a specific location (grid cell or stream location)
- No emergence by 2100 for a particular combination of threshold and slope for a specific input model
- No occurrence (i.e., exceedance of the threshold) during the historical reference period for a specific input model

Reasons for flagging a variable as “non-emergent” for spatially-aggregated ToE results for an individual model
- Less than 60% of the grid cells in the selected spatial unit show emergence by 2100
- Disagreement over direction of climate change signal among grid cells in the selected spatial unit showing emergence prior to 2100

Reasons for flagging a variable as “non-emergent” for multi-model spatially-aggregated ToE results (e.g., ToE at 25%, 50% (multi-model median), and 75% model agreement)
- Less than 25%, 50% or 75% agreement on the direction of the climate change signal within the original ensemble of climate models considered for the spatially-aggregated ToEs
- Fewer than 25%, 50% or 75% of the spatially-aggregated ToEs show emergence by 2100

To test the method, we first applied the ToE computation to global fields of standard extreme climate indices computed by the Expert Team on Climate Change Detection and Indices (ETCCDI). This suite of indices provided an opportunity to test the robustness of the method with variables that have substantially different climate sensitivities from each other and across the globe. Results from this analysis will be reported in a publication now in draft form, which constitutes one of the publications resulting from this project. Regional results from this test dataset show robust model agreement that for PNW temperature-based extremes, ToE is likely in the next 50 years. For precipitation-based extremes, ToE projections are later, but there is good general agreement in direction of change for ToE calculations.
2.5 Post processing

2.5.1 Spatial Aggregation

Aggregation from grid cell data to spatial units was requested by stakeholders, and we selected two aggregation units: 1) Counties in WA, OR, and ID and 2) 4th-Level (8-digit) hydrological unit codes (HUCs) within HUC region 17. These spatial units were chosen in part because they are spatially small enough to provide useful results. Due to the high spatial resolution of the gridded data and topographic heterogeneity across the PNW, a spatial unit significantly larger than a typical county would encompass too wide a range of date of emergence and disparities in the direction and magnitude of the climate trend.

Spatial aggregation was first done for each variable, scenario, tolerance level, confidence level, and model. To ensure that the aggregated results reasonably reflect the Time of Emergence within the spatial unit, two criteria had to be met prior to a real averaging:

1. All grid cells indicating emergence in that variable agree in the direction of change in that variable. We do not report ToE when there is disagreement in the trend direction – for a particular model, scenario, sensitivity, etc. – because assigning a date of emergence makes no sense without clarity about whether the variable is expected to increase or decrease.

2. The signal has emerged by 2100 in at least 60% of the grid cells in the selected spatial unit. This criteria assures that a majority of the region has an emergent trend. We do not require emergence in 100% of the grid cells (as above) because lack of emergence is not a physical contradiction as are differences in trend direction.

If both of the above mentioned criteria are met, data were aggregated across the spatial unit. If either of the above criteria was not met, the ToE for that spatial unit would be reported as non-emergent (Table 6). For streamflow data, the spatial aggregation step is

\[\text{http://water.usgs.gov/GIS/huc_name.html#Region17}\]
not needed because streamflow results are based on gauge station information, which are discrete points and not gridded values.

After areal averaging was completed for each variable, scenario, tolerance (threshold) level, confidence level, and model, model agreement was calculated for each variable, scenario, tolerance level, and confidence level at each spatial unit. This was done to represent the ensemble consensus for the spatial unit. As with the gridded results, to understand ensemble spread in ToE, we calculated the year at which 25, 50, and 75% of all models in the ensemble have ‘emerged’. For example, 16 of the models in the 21-model BCSD5 ensemble have emerged by 2060 for a given spatial unit, the ToE for 75% model agreement is set to 2060.
3 Prototype Online Tool

3.1 Introduction
The prototype Time of Emergence tool is an interactive web-based platform developed to support climate change risk assessment and decision-making by providing user-friendly access to Time of Emergence results. The tool is designed to enable users to explore when and where climate change could matter, to support prioritization of preparatory action to reduce climate risks or climate impacts. The tool is also intended to help engender deeper understanding among users of the existing range in assessments of the location and timing of significant climate impacts, and the sensitivity of such results to reasonable alternative choices about potential future conditions and user sensitivity to change. This section describes the organization and content of the prototype tool as currently implemented on the ToE test server at http://timeofe.cloudapp.net/\(^5\), as well as website specifications.

3.2 Content

3.2.1 Site Organization
The prototype Time of Emergence tool (Figure 4) enables the user to:

- **READ** about the “Time of Emergence” concept and methodology,
- View a pair of introductory **TUTORIALS** illustrating use of the tool, and
- **EXPLORE** the Time of Emergence of decision-relevant climate change by locale or by variable, and the sensitivity of such results to reasonable alternative choices about potential future conditions and user sensitivity to change.

\(^5\) Although efforts have been made to ensure consistency between this document and the prototype website, in cases where there appear to be discrepancies between the two, the website should be considered to be correct.
Figure 4. Organization of the prototype Time of Emergence online tool.
3.2.2 User exploration of Time of Emergence results

The “explore” section of the prototype online tool allows the user to view the Time of Emergence of decision-relevant climate change by locale or by variable, and to explore the sensitivity of the results due to the associated uncertainties, based on the methodology and models applied. This occurs through a series of user-oriented queries as illustrated in Figure 5 and described below.

![Figure 5. Organization of the “Explore” section of the prototype Time of Emergence online tool.](image)
3.2.2.1 Explore by locale

In this part of the tool (the left branch in Figure 5), the user can explore the question: *Which type of changes could occur first?* by comparing ToE results for a set of variables in a specific sub-domain (county, watershed, stream location) within the Pacific Northwest. This part of the tool also helps the user evaluate *How uncertain are these projections?* by exploring how the results change under different assumptions about potential future change and the ability of the management system to cope with that change.

3.3.1.1 User selection of locale, variables, analytical parameters

The user can select a particular location of interest (county, watershed (4th-level (8-digit) hydrologic unit code) or river location) within the Pacific Northwest (Washington, Oregon, Idaho, and the British Columbia portion of the Columbia River basin) for which to compare results for two or more hydro-climatic variables. The user selects the hydro-climatic variables of interest, either from a drop-down list of all available variables, or using a filtering tool that generates a shorter list of variables within specified categories. The available filter options are listed in Table 7; the categorization of variables by filter category is shown in Table 8.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Related Impact</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>• All</td>
<td>• All</td>
<td>• All</td>
</tr>
<tr>
<td>• Air Temperature</td>
<td>• Drought</td>
<td>• Average</td>
</tr>
<tr>
<td>• Precipitation</td>
<td>• Energy</td>
<td>• Extreme</td>
</tr>
<tr>
<td>• Hydrologic</td>
<td>• Fish</td>
<td>• Monthly or seasonal</td>
</tr>
<tr>
<td>• Streamflow</td>
<td>• Flood</td>
<td>• Annual</td>
</tr>
<tr>
<td></td>
<td>• General</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Human health</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Infrastructure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Streamflow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Water quality</td>
<td></td>
</tr>
</tbody>
</table>
### Table 8. Categorization of Variable

<table>
<thead>
<tr>
<th>Theme</th>
<th>Descriptor</th>
<th>Impact</th>
<th>Timescale</th>
<th>Variable name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>Average</td>
<td>Human health</td>
<td>Monthly</td>
<td>Temperature, each calendar month</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Extreme</td>
<td>Human health / Energy supply</td>
<td>Monthly</td>
<td>Number of days with daily maximum temperature above 65°F (18.3°C), March-November</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Extreme</td>
<td>Human health / Energy supply</td>
<td>Seasonal</td>
<td>Number of days with daily average temperature below 25°F (~3.9°C), winter (Dec-Feb)</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Extreme</td>
<td>Human health / Energy supply</td>
<td>Seasonal</td>
<td>Number of days with daily average temperature above 68°F (20°C), spring (Mar-May) and fall (Sep-Nov)</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Extreme</td>
<td>Human health / Energy supply</td>
<td>Annual</td>
<td>Number of days with daily maximum temperature above 90°F (32.2°C), annual</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Extreme</td>
<td>Human health / Energy supply</td>
<td>Seasonal</td>
<td>Number of days with daily maximum temperature at or above 80°F (26.7°C), spring-summer (21 April-21 August)</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Extreme</td>
<td>Human health / Energy supply</td>
<td>Annual</td>
<td>Number of daytime heat waves (3 consecutive days with daily maximum temperature above historical 99th percentile), annual</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Extreme</td>
<td>Human health / Energy supply</td>
<td>Annual</td>
<td>Number of nighttime heat waves (3 consecutive days with daily minimum temperature above historical 99th percentile), annual</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Average</td>
<td>Water availability</td>
<td>Monthly</td>
<td>Precipitation, each calendar month</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Average</td>
<td>Water availability / Flood / Fish</td>
<td>Seasonal</td>
<td>Precipitation, fall (Oct-Dec), winter (Jan-Mar), spring (Apr-June), summer (Jul-Sept)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Extreme</td>
<td>Flood / Fish / Landslide</td>
<td>Seasonal</td>
<td>Number of days with 24-hour precipitation exceeding historical 90th, 95th and 99th percentile, October-March</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Extreme</td>
<td>Flood / Fish / Landslide</td>
<td>Annual</td>
<td>Number of days with 24-hour precipitation exceeding 2 inches (50.8 mm), annual</td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
<td>--------------------------</td>
<td>--------</td>
<td>---------------------------------------------------------------------</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Extreme</td>
<td>Flood / Fish / Landslide</td>
<td>Annual</td>
<td>Maximum 48-hour precipitation accumulation, annual</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Extreme</td>
<td>Flood / Fish / Landslide</td>
<td>Annual</td>
<td>Maximum 24-hour precipitation accumulation, annual</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Extreme</td>
<td>Flood / Fish / Landslide</td>
<td>Annual</td>
<td>Number of days with 24-hour precipitation equal to 3 inches (76.2 mm) or more, annual</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Extreme</td>
<td>Flood / Fish / Landslide</td>
<td>Seasonal</td>
<td>Number of wet sequences (18-day cumulative precipitation exceeding 3.5 inches (88.9 mm)), October-March</td>
</tr>
<tr>
<td>Hydrologic</td>
<td>Average</td>
<td>Water availability</td>
<td>Annual</td>
<td>Runoff, annual</td>
</tr>
<tr>
<td>Hydrologic</td>
<td>Average</td>
<td>Water availability / Flood / Fish</td>
<td>Monthly</td>
<td>Runoff, each calendar month</td>
</tr>
<tr>
<td>Hydrologic</td>
<td>Average</td>
<td>Drought / Water availability / Water quality</td>
<td>Monthly</td>
<td>Dryness Ratio, each calendar month</td>
</tr>
<tr>
<td>Hydrologic</td>
<td>Average</td>
<td>Drought / Water availability / Water quality</td>
<td>Monthly</td>
<td>Potential evapotranspiration (PET), each calendar month</td>
</tr>
<tr>
<td>Hydrologic</td>
<td>Average</td>
<td>Drought / Water availability / Water quality</td>
<td>Monthly</td>
<td>Actual evapotranspiration (AET), each calendar month</td>
</tr>
<tr>
<td>Hydrologic</td>
<td>Average</td>
<td>Drought / Landslide</td>
<td>Monthly</td>
<td>Soil moisture, each calendar month</td>
</tr>
<tr>
<td>Hydrologic</td>
<td>Average</td>
<td>Water availability</td>
<td>Monthly</td>
<td>Snow water equivalent (SWE), each calendar month</td>
</tr>
<tr>
<td>Hydrologic</td>
<td>Extreme</td>
<td>Water availability</td>
<td>Annual</td>
<td>Coefficient of variation of runoff, annual</td>
</tr>
<tr>
<td>Hydrologic</td>
<td>Extreme</td>
<td>Flood / Fish</td>
<td>Annual</td>
<td>Highest spring runoff date</td>
</tr>
<tr>
<td>Streamflow</td>
<td>Average</td>
<td>Water availability / Water quality</td>
<td>Monthly</td>
<td>Streamflow, each calendar month</td>
</tr>
<tr>
<td>Streamflow</td>
<td>Average</td>
<td>Water availability</td>
<td>Annual</td>
<td>Streamflow center of timing</td>
</tr>
<tr>
<td>Streamflow</td>
<td>Extreme</td>
<td>Flood / Fish</td>
<td>Annual</td>
<td>Maximum daily streamflow per year</td>
</tr>
<tr>
<td>Streamflow</td>
<td>Extreme</td>
<td>Flood / Fish</td>
<td>Monthly</td>
<td>Maximum daily streamflow, each calendar month</td>
</tr>
<tr>
<td>Streamflow</td>
<td>Extreme</td>
<td>Flood / Fish</td>
<td>Annual</td>
<td>Number of flood flows per year</td>
</tr>
</tbody>
</table>
The user can then select the input parameters necessary for calculating ToE – i.e., emissions scenario, estimated rate of climate change and management sensitivity – or to accept the system defaults (high emissions, low sensitivity, moderate rate of change).

Specifically, the user can select the input parameters for:

- **Emission Scenario**
  The user can select a “High” (RCP8.5 and SRES A1B) or “Low” (RCP4.5 and SRES B1) emissions scenario. “High” implies an earlier ToE estimate due to greater effects of climate change; “Low” implies a later ToE estimate due to smaller effects. The two sets of emissions scenarios (RCP and SRES scenarios) are noted for the user since ToE results are provided from climate data sets derived from CMIP5 and CMIP3, respectively. The user can find more details about the definition and selection of emission scenario in the “read” section of the website.

- **Management Sensitivity**
  The user can select a “High” or “Low” level of management sensitivity to past hydro-climatic fluctuations or extreme events. “High” sensitivity represents a management system that would experience negative impacts during the most extreme 20% high or 20% low conditions that occurred for the variable of interest during the 1950-1999 reference period. “Low” sensitivity represents a system that would experience negative impacts during only the most extreme 5% high or 5% low conditions. Therefore, “High” sensitivity leads to an earlier ToE estimate due to less tolerance for extreme conditions; “Low” leads to a later ToE estimate due to higher tolerance.
• **Estimated Rate of Climate Change**

The user can choose to view results based on a “Fast”, “Moderate” or “Slow” estimate of the rate of climate change. This describes the rate of climate change estimated from any particular global climate model (i.e., the calculation of the slope of the climate change signal, as described previously). “Fast” implies an earlier ToE estimate due to more rapid climate change; “Slow” implies a later ToE estimate due to less rapid climate change; and, “Moderate” implies a ToE estimate roughly centered between “Fast” and “Slow” due to moderate climate change. For each global climate model, the values provided are within the 90% confidence range, i.e., there is a 5% chance that the true rate of climate change could occur faster than the “Fast” rate, and there is a 5% chance that the true rate could occur slower than the “Slow” rate.

All results for temperature and precipitation-related variables available through this part of the tool were derived from the BCSD5 dataset; (gridded) hydrologic results were derived from BCSD3. Where available, streamflow-related variables were derived from the BCSD5 dataset (i.e., sites denoted “CMIP5” or “Both) in Figure 2); to increase spatial coverage, ToE results for streamflow-related variables derived from the BCSD3 dataset are provided for additional river locations (i.e., sites denoted “CMIP3” in Figure 2). Source dataset is indicated as part of the variable label on the timeline visualization (e.g., Figure 6) and in the title of the dot-plot visualization (see Figure 7).

In both the “Read” section of the online tool and the User Guide, we provide guidance on using information about specific management contexts and risk tolerance to choose parameters and interpret ToE results, as outlined in Table 9.
Table 9. Guidance on Input Parameter Selection

<table>
<thead>
<tr>
<th></th>
<th>Lower Risk Tolerance</th>
<th>Higher Risk Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Scenario</td>
<td>High (RCP8.5 or SRES A1B)</td>
<td>Low (RCP4.5 or SRES B1)</td>
</tr>
<tr>
<td>Management sensitivity</td>
<td>High (impacts triggered by most extreme 20% high or 20% low of past (1950-1999) conditions)</td>
<td>Low (impacts triggered by most extreme 5% high or 5% low of past (1950-1999) conditions)</td>
</tr>
<tr>
<td>Rate of Climate Change</td>
<td>Fast (earlier ToE)</td>
<td>Slow (later ToE)</td>
</tr>
<tr>
<td>Model Agreement EXPLORE by Variable only</td>
<td>Low (25%)</td>
<td>High (75%)</td>
</tr>
</tbody>
</table>

3.3.1.2 Visualization of results

After entering the selections described above, the online tool dynamically generates and delivers a graphical visualization and tabular summary of ToE results for the specified location, variables, and analytical parameters. A timeline graphically depicts the sequence of occurrences between 2000 and 2100 of the central estimates of the Time of Emergence (denoted by the multi-model median value) for the selected variables across all the global climate models examined (Figure 6). Due to space constraints, shortened variable names are displayed on the timeline. Succinct information about interpreting the timeline results is displayed onscreen; more details are provided in both the “Read” section of the online tool and the User Guide.

Figure 6. Sample timeline from the prototype online tool showing multi-model median ToE for (left to right) annual number of daytime heat waves (three consecutive days with daily maximum temperature above historical 99th percentile), average April temperature, and number of days in July with daily maximum temperature above 65 degrees F. Results are shown for King County for High emissions, Low sensitivity, Fast rate of change, from the BCSD5 dataset. Both the image (PNG format) and data (CSV format) are easily available for export by the user by way of the onscreen Export buttons.
In addition to the multi-model median ToE shown in the timeline, the online tool dynamically generates a tabular summary of the plausible range of ToE results for each variable depicted on the timeline (Figure 7). The ranges represent the central 50% of the range of emergence dates projected by the ensemble of climate models considered. That is, based on uncertainty in simulating future climate (represented by the multi-model ensemble), there is a 50% chance that this range indicates the time when future conditions are projected to deviate from those experienced in 1950-1999, for the displayed variables according to the selected emission scenario, past sensitivity and rate of climate change. (There is a 25% chance that emergence will occur earlier than indicated, and a 25% chance that it will occur later than indicated.)

![Table of Estimated Range of Time of Emergence for WA - King Under High (RCP8.5 or A1B)](image)

**Figure 7.** Sample results table from the prototype online tool showing the central 50% of the multi-model projected range of ToE for (top to bottom) average April temperature, annual number of daytime heat waves (3 consecutive days with daily maximum temperature above historical 99th percentile), and number of days in July with daily maximum temperature above 65 degF. As in Figure 6, results are shown for King County for High emissions, Low sensitivity, Fast rate of change, from the BCSD5 dataset.

The user can explore the effects of uncertainty in the analytical parameters by selecting different options for emission scenario, management sensitivity and rate of climate change in the onscreen query dialog box at any time, clicking the *Show Results* button, viewing the dynamically-updated results in the timeline and table, and downloading the updated image and data files.
For more detailed information about the effects on estimated ToE of alternative choices about analytical parameters for any specific variable, the user can generate a database query by clicking on any “see details” for any one of the hydro-climatic variables listed in the table. The prototype online tool dynamically generates a set of figures illustrating the complete range of ToE results for the specific variable and location – that is, the spread of ToE results arising from the different global climate models, emission scenarios, management sensitivity and rates of climate change. These figures indicate dates of emergence prior to 2100 for each climate model indicating emergence, the direction of change in the variable associated with each model ToE, the multi-model median date of emergence (the date at which 50% of the models in the set of climate models examined indicate emergence), and the direction of change in the variable associated with the multi-model median date of emergence.6

The resultant scatter plots (Figure 8) illustrate the effects of uncertainties associated with:

1. Rate of climate change, estimated from each global climate model simulation – represented by the three colors. The rate of change for each model falls within this range with 90% confidence and reflects statistical uncertainty.

2. Climate modeling, estimated using output from different global climate models – represented by the horizontal spread of symbols. Each model should be considered equally probable, and the range reflects uncertainties in modeling the climate system.

3. Future emissions, estimated using two emissions scenarios – represented by the left and right panels. These scenarios depend on specific policy actions and represent uncertainty in future societal choices.

4. Definition of the threshold for emergence of significant climate change, estimated using two levels of management sensitivity to past climate

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6 When models disagree on the direction of change in a variable, the multi-model median ToE is calculated as follows. For ToE of a positive trend, all models w/ negative trend are given an infinite ToE before median is determined. For ToE of a negative trend, all models w/ positive trend are given an infinite ToE before median is determined. Therefore, by construction, there can be only one non-infinite multi-model median ToE, which corresponds to the direction of trend shown by the majority of models.
fluctuations – represented by the top and bottom panels. These choices reflect uncertainty in the vulnerability of human and natural systems to past and future climate fluctuations.
Figure 8. Sample plots from the prototype online tool showing ToE for average April temperature in King County projected by each model simulation for all parameter choices. Left and right panels: High and Low emissions, respectively; Top and bottom panels: High and Low sensitivity, respectively; Three colors: estimated fast, central, and slow rate of climate change, represented by purple, green and orange, respectively. For this variable, results are derived from the BCSD5 dataset.
The data (CSV format) are easily available for export by the user, via the onscreen Export buttons.

3.2.2.2 Explore by variable
In this part of the tool (the right branch in Figure 5), the user can explore the question: Where could changes occur first? for a specific variable of interest – across either the entire Pacific Northwest domain or within the Puget Sound basin. This part of the tool will also help the user evaluate How uncertain are these projections? by exploring how the results change under different assumptions about potential future change and the ability of the management system to cope with that change.

3.2.2.2.1 User selection of locale, variables, analytical parameters
The user can select a variable of interest (from the entire list, or a subset generated using the filtering tool described above) and select one of two map types to view:

- Year of Emergence – showing the average (multi-model median) time when future conditions are projected to deviate from those experienced in 1950-1999 (for grid cells with at least 60% agreement among global climate models in the direction of the climate change signal; multi-model median is computed as described in the previous section).
- Emergence locations – showing places where global climate models project future conditions to deviate from those experienced in 1950-1999, for a moderate rate of climate change and four future time periods (by 2025, 2050, 2075 and 2100), according to three levels of global climate model agreement (25%, 50%, 75%).

The user can select the geographic domain of interest (the Puget Sound basin or the Pacific Northwest (states of WA, OR, ID and the BC portion of the Columbia River basin)), emissions scenario and management sensitivity (as described above), climate dataset (Table 10), and desired boundaries for maps overlay (state, county, or watershed (4th-level (8-digit) HUC). Because uncertainty in the estimated rate of climate change is
unlikely to affect the spatial pattern of ToE, all maps were developed using the central estimate for the rate of climate change.

<table>
<thead>
<tr>
<th>Temperature &amp; Precipitation Variables</th>
<th>Hydrology Variables</th>
<th>Streamflow Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCSD5</td>
<td>BCSD3</td>
<td>BCSD5</td>
</tr>
<tr>
<td>ECHAM5-WRF</td>
<td>BCSD3</td>
<td>BCSD3</td>
</tr>
</tbody>
</table>

3.2.2.2.2 Visualization of results

After entering the selections described above, the prototype online tool queries a catalog of pre-generated images and displays the map corresponding to the user’s selection (Figures 9 and 10). Succinct information about interpreting the maps is displayed onscreen; more details are provided in both the “Read” section of the online tool and the User Guide. The images (PNG format) are easily available for export by the user.
Figure 9. Sample map of “Year of Emergence”, depicting where and when there are projected to be noticeable differences in number of days per year with daily maximum temperature exceeding 90°F (32.2°C) compared to 1950-1999, for High management sensitivity, High emissions, and a Moderate rate of climate change, as derived from the BCSD5 climate dataset. Results are shown for the multi-model median ToE across the 21 global climate models examined at each grid cell in the domain. At each grid cell, therefore, the indicated date represents when 50% of the 21 global climate models examined project the climate change signal to have emerged for the given set of analytical parameters.
Figure 10. Sample map of “Emergence Locations”, depicting where there are projected to be noticeable differences in the annual coefficient of variation of runoff by 2075 compared to that experienced in 1950-1999, for High management sensitivity, High emissions and a Moderate rate of climate change, according to the BCSD3 climate dataset. The different shadings indicate where 25%, 50% and 75% of the six global climate models examined agree that the signal will have emerged by 2075.
3.2.3 Read

This section provides a brief description of the prototype online tool, as well as scientific and technical information on:

- The concept of Time of Emergence of climate change, including the methodology applied to determine ToE, its relevance and usage
- The available hydro-climatic variables, how they were identified, defined, and calculated
- Uncertainties associated with the ToE results, including those arising from climate modeling, and ToE estimation
- Background on the input datasets used for ToE analysis

The “read” section also provides a log of any identified bugs in the online tool and a catalog of frequently asked questions and responses, to provide the interested user more details about the underlying methods, assumptions, datasets, interpretation, and application of the ToE results. The following subjects are covered within the FAQ:

**Informing Decisions with Time of Emergence Information**
- Climate change projections are already available for many variables. What added value is provided by Time of Emergence analysis?
- How can I use information about Time of Emergence?
- Does this tool provide all the information I need to prepare for climate risks?
- Are other climate change decision-support tools available?
- Why are some variables (e.g., stream temperature) not included in the analysis?

**Factors Affecting Projected Time of Emergence**
- Why are there different rates of climate change?
- Which emission scenario, management sensitivity, rate of climate change or model agreement should I choose?
- Why does this tool provide more than one Time of Emergence for a given variable and location?
• Are all the modeling uncertainties accounted for in this Time of Emergence analysis?

Interpreting Results
• How should I interpret the maps?
• Are the GCMs used weighted when generating ensemble results?
• Why are the results from a single projection (e.g., a single climate model run with a specific emission scenario) not available?
• Why is the multi-model average value represented by the median rather than the mean?
• Why are the most extreme values of the ensemble not provided in the results?
• What is “GCM agreement”?
• Does the “percentage of GCM agreement” translate to the “probability”, of something occurring in future?
• Why is the “probability”, of something occurring in future not estimated?
• Why are the results simply presented as “GCM agreement”, and why have no other more sophisticated statistical methods have been applied?
• Given the uncertainties in the underlying climate projections, are projections of the Time of Emergence of climate change still useful for planning purposes?
• Why is the exact year and location (at the grid cell scale) of the Time of Emergence not provided?
• What are some of the main assumptions associated with the Time of Emergence projections presented in this tool?

Use of Products
• How do I acknowledge use of the results, data and products available from this tool?
Methods

- What is the baseline period for defining the management sensitivity (“noise”) component in this analysis?
- How is the climate change signal defined in this analysis?
- Why was the signal threshold method chosen instead of other approaches?

Science and Modeling

- What is a climate projection, or a climate simulation?
- What is the difference between a “climate projection” and a “climate prediction”?
- What is an emission scenario?
- What is a climate model?
- What is downscaling?
- What is a multi-model ensemble?
- What is uncertainty in climate projections?
- What is modeling uncertainty?

3.2.4 Tutorial

This section provides two examples of how a user might use the tool to support climate change decision-making: one for “EXPLORE by locale” and one for “EXPLORE by variable”. These guided tours demonstrate how a user might navigate the tool to generate customized results and images, what input parameters s/he might select, and the interpretation of the results.

3.3 User Feedback

In addition to soliciting feedback from the project funders on the prototype website design throughout the course of the project, input on the beta version of the prototype tool was solicited from a broader group of regional stakeholders. Stakeholders invited to review the beta site included: EPA and USACE (review coordinated by Jon Schweiss), and regional stakeholders previously contacted about the ToE project (e.g., during
solicitation of input for variable selection), including managers, planners, and resource managers at:

- Federal agencies: USEPA, USACE, U.S. Department of Interior Bureau of Reclamation (USBR), U.S. Forest Service (USFS), US DOI Northwest Climate Science Center
- State agencies: Washington State Departments of Health (WADOH), Ecology, Natural Resources, Transportation (WSDOT), Emergency Management Division (EMD), and the Puget Sound Partnership (PSP)
- Local agencies: King County, City of Seattle
- Tribes: Swinomish, Puyallup, Tulalip, Yakama, Quinault, Northwest Indian Fisheries Commission

Reviewers were asked to comment on site usability, including value of information delivered, clarity and understandability of depiction and description of results, navigation, quality of introductory (“Tutorial”) and more detailed background (“Read”) materials. Feedback was received from the entities indicated in bold in the list above.

The general assessment of the usability and value of the site was positive as exemplified by the following comments from reviewers:

- “This is a great start for a tool that I would think could be helpful to many people.”
- “Overall, this website is well-conceived and provides a new accessibility to climate change predictions as intended. I found the exploration options to be very interesting. In particular, I was pleased by the ability to select multiple variables at once to compare emergence on a single timeline (such as what months/seasons show change first).”
- “This is a creative website, and it works reasonably well with a little practice. It is better than most sites that require you to download data and make your own maps and develop your own inferences.”
- “Overall, this is a really cool interactive tool. Well done.”
• “I am able to incorporate this type of information into my preparation work here at King County. I find that when I talk with folks here in King County about preparing for climate change, it is beneficial to discuss multiple aspects of change. These multiple aspects include the current conditions and variability in conditions and the timing of different magnitudes of change. For example, when talking with folks at King County Public Health, I talk about current average and distribution of the number of 90 degree days per year, and the rate of increase in the number of 90 degree days per year over the next century. The time of emergence website provides a piece of the information puzzle which is useful.”
• “There is so much truly useful data available here, I look forward to looking through it more thoroughly.”

Other general comments indicated a desire for more interpretation and assistance with use of the site, especially for less technical users:
• “Overall, I think that this is a fun and useful tool for scientists and laymen to explore regional impacts from climate change, but I think that there should be more clarity in the what and why it is slicing and dicing the data the way it is.”
• “I would like to have more interpretation of results.”
• “It would have been nice to have hyperlinks to some basic information in some places (e.g., when asked to select an emissions scenario, I couldn’t remember the parameters of each).”
• “Overall, this website seems geared to somebody who knows a fair bit about climate change modeling, though not necessarily a modeler. I would suspect that somebody less knowledgeable than me on this topic would struggle to use this website. I say this because of the technical decisions needed in selecting what to evaluate, and the specific way emergence is defined based on model convergence. As currently configured and presented, I would not recommend this website to planners or policy makers without somebody providing guidance.”
• “I am not sure who your target audience is. If it is a broad public and laypersons, I hope you will add more user-friendly translations. I’d recommend beefing up the
tour so you can help users understand what the results show (or how to really get to the key take-a-ways).”

In addition to these general comments, numerous detailed and thoughtful suggestions were provided for nearly every page on the site, with a high focus, as requested, on the interactive “Explore” section.

3.3.1 Post-review Revisions

Given the limited time and resources for web development in this phase of the project, revisions of the prototype online tool in response to the beta review were prioritized as follows:

1. Revisions necessary to ensure that the prototype tool accurately delivers and represents Time of Emergence results, e.g.:
   - Revised timeline query logic (to enable display of BCSD3-derived results for river sites where BCSD5 results are not available)
   - Revised calculation, display, and description of (multi-model median) timeline results (to improve consistency with summary dot plot displays and mapped emergence location results, correct offsets between exported and displayed data, and provide complete documentation of the query parameters used to generate the timeline)
   - Revised maps of emergence year (multi-model median ToE) to improve consistency with timeline, summary dot plot displays and mapped emergence location results
   - Corrected error in calculation of ToE for nighttime heat waves
   - Revised maps query logic (to accommodate multiple climate dataset options for different subsets of variables (see Table 10), disallow choice of emissions scenario for WRF results (only available for “High” emissions) and correct disparities between user-selected Management Sensitivity and actual map returned)
   - Remade all maps (to correct color offset between map and legend, correct a bug that had caused all of the ECHAM5-WRF maps of
temperature variables to be identical on the beta site, add legend
description for boundaries)

- Provided more detailed information about the full range of ToE results
  for a given variable and location, by
  - Adding the multi-model median value to the summary dot-plots
  - Enhancing symbology of summary dot-plots to indicate direction
    of trend for each ToE

2. Revisions requested to improve user experience (navigation, interpretation,
supporting information), with a focus on revisions pertaining to the
functionality of the site, e.g.:

- Revised drop-down menu listings of specific watersheds and river
  locations (to group geographically and include HUC and USGS gauge
  identifiers)

- Improved error trapping (including onscreen error messages for
  various user errors, and provision of additional onscreen information
  when user-selected combination of parameters leads to no results on
  the timeline)

- Improved between-page navigation (including highlighting of option
  to navigate to the All Results Plot page for more details than provided
  on the timeline page, navigation options for leaving the All Results
  Plot page, support for sequential navigation of “Read” and “Tutorial”
  pages)

- Improved layout (including revision of the site template to provide
  more screen space ToE results and reduce need to scroll, larger maps
  to enhance legibility)

- Improved home page and site navigation layout to benefit the novice
  user (including a brief introduction to the site and re-ordering and re-
  naming of main site sections)

- Provided more details about methods of variable calculation (to
  support inter-comparison with existing metrics; in “Read” section)
• Various other requested improvements, bug fixes and broken links (e.g., new map at start of “Explore”, fixed database bug that created the “Fis” impact listing in the variable filtering dialog box, instructions for controlling maps slideshows, modifications to variable classifications (under “theme” in the variable filtering dialog box), fixed truncation and incorrect symbols for some variable names on timeline display)

3.3.2 Potential Future Refinements
Additional refinements suggested by the beta reviewers are noted here for consideration as possibilities for enhancing the online tool in future project phases. These include:

• Further testing and refinement of the language used to indicate management sensitivity to climatic fluctuations and change. Several reviewers found the term “Management Sensitivity” confusing. Part of the confusion was due to inconsistent use of terminology across the site, but it also likely reflects the difficulty of capturing multiple important aspects of the management-specific dimensions of emergence in a single phrase. Explicitly testing a variety of alternate terms with a range of users is recommended for reducing this confusion.

• Providing enhanced interpretation and user assistance to support both novice and technical users.
  o Several reviewers commented that the current implementation of the site could be difficult to navigate for non-technical users, including planners and policy makers, but that the content would be of interest to those groups as well. Additional “user-friendly translations” of the analyses, assumptions, results and implications were one suggestion for enabling engagement with a broader set of users.
  o Reviewers provided a variety of suggestions for increasing the availability of technical detail – throughout the “Explore” section – in order to support deeper understanding by technical users of the site.
  o As reviewers explored the range of ToE results, a variety of questions arose regarding the implications of these findings for their decision and
planning contexts. We anticipate that successful uptake of these results will be improved by ongoing technical support for users, and by further analysis and discussion between scientists and practitioners of the significance and implications of the results, in particular as they relate to specific climate change risk assessment contexts.

- Continued refinement of onscreen instructions, sequencing and layout of dialog/query selection boxes, navigation within the Explore section and links to additional supporting or interpretive information.
- Addition of new variables and datasets
- Development of additional functionalities. Reviewers identified numerous potential future functionalities. In the interest of space, we highlight only a few here:
  - In addition to ToE results, provide information about the actual magnitudes for the variables, and how these are changing over time
  - Enable more user control (user ability to select custom month/seasonal ranges for specific variables, set variable thresholds (e.g., for temperature thresholds above XX degrees))
  - Provide detail about the specific reason for “no emergence”
  - Provide users with the ability to show and compare multiple timeline and/or map results (reflecting different choices) for one or more variables and to easily navigate between related timeline/dot-plots and maps.

### 3.4 Website Architecture

#### 3.4.1 Overall Architecture

The Time of Emergence Prototype website provides the capability to query, retrieve and extract Time of Emergence results computed by the Climate Impacts Group. The developed system leverages existing open source frameworks that provide basic website navigation constructs, augmented with custom development to enable the requested data flows, and visualizations as identified by project stakeholders. This approach enables
targeting of scarce resources on specific needs of the project, while leveraging generally accepted web development approaches and capabilities of the underlying framework.

### 3.4.2 Underling Framework

The underlying framework of the site consists of several components. The core functional elements (authentication, content management file handling, etc.) are handled through the standard Drupal Content Management System (CMS). This system is widely deployed and used by such entities as UW.edu and WhiteHouse.gov. Additional custom modules were developed to provide the advanced filtering capability, and serve up the requested visualizations. The customizations have been developed using standard Drupal programming practices and coding conventions (https://www.drupal.org/coding-standards).

### 3.4.3 Data Engine

The underlying database engine for the site is MySQL, a standard open source database used in many web applications. This database engine powers both the underlying database for the Drupal site, which controls logic for items such as user management and navigation, as well as a separate database which manages and serves the climate data. This separation is seamless to the end user as the system internally handles switching between the two data sources.

This separation allows system administrators to handle standard Drupal management and automated upgrade protocols, while providing undisturbed access to the data. This also makes it easier for migration of the results to another system, should that become necessary.

Information about Drupal API’s and schema can be found on Drupal.org (https://api.drupal.org/api/drupal).

### 3.4.4 Data Extraction / Download

There are two types visualizations on the site, on demand and pre-generated.
The timeline and summary dot-plot visualizations are generated on demand, based on input from the user and the available underlying data. The generated images themselves and the underlying data can be downloaded; the latter extracted to industry standard CSV format for easy sharing and transfer of the data.

The pre-generated map data is represented as images that the user will be able to download using a standard right or ctrl click.

3.4.5 Hosting Environment and Installation instructions

3.4.5.1 Hosting
For development the system was installed on a standard open source LAMP stack framework, (Linux, Apache, MySQL, PHP) which was hosted on the Microsoft Azure cloud hosting service. The delivered code will consist of the system files, custom code, as well as two database snapshots (Drupal core, and custom TOE data databases). This will be delivered either through the online source control repository (https://github.com/WebDataScience/cwds-time-of-emergence) or as a compressed file.

3.4.5.2 Installation
An industry professional with moderate exposure to LAMP stack and Drupal development will be able to deploy the site to any standard LAMP based system.
4 Incorporating Uncertainty in Computing and Communicating Time of Emergence

There are many caveats to using climate models and climate model projections, and it is necessary to address the issue of ‘uncertainty’ in particular. From the literature, uncertainty in global climate change projections is described as a measure of variation among model projections due to emissions scenario used, model response/sensitivity, and natural variability (Hawkins and Sutton 2009). For local projections, uncertainty also results from downscaling and subsequent impacts modeling, such as hydrologic simulations to develop projections for future hydrologic conditions. For this project, uncertainty also arises from numerical probability assessments, which exists due to our methods of calculating Time of Emergence (ToE) of the climate change signal. This type of uncertainty is usually examined through error statistics and confidence estimates (Katz et al. 2013). Here we discuss each component of uncertainty in turn.

A primary limitation in understanding uncertainty in climate projections compared to weather or seasonal (e.g., ENSO) forecasting is that we cannot produce calibrated probability estimates based on past performance. For example, in weather forecasting, a forecast of an 80% chance of an event can be interpreted as meaning: In the past ten times when a similar model outcome was obtained, the forecasted event occurred eight times. Thus, if a user consistently followed this forecast guidance, 20% of the time they would have made the wrong choice. In the case of climate projections, we cannot use this sort of interpretation -- even when similar numerical values could be computed. In particular, the uncertainty in emissions scenario depends on societal choices that cannot be given a reasonable statistical interpretation. Instead, we recommend that the source of uncertainty be made clear with statements like 80% of the models show ToE before this date or the ToE is in a given time interval, based on a 90% confidence estimate of the climate trend.

The uncertainty due to emission scenario used cannot be eliminated, as future socio-economic conditions are unknown, but we can examine multiple emission scenarios to look at a range of possible future outcomes. We examined this type of uncertainty by using both the RCP4.5 and RCP8.5 emission scenarios used in CMIP5, and the SRES B2
and A1B emission scenarios used in CMIP3. The selection of these scenarios was based on the combination of availability of simulations based on specific scenarios, and the desire to span the range of available scenarios. Certain emission scenarios in both CMIP3 and CMIP5 were given higher priority by the IPCC, which limited the number of available climate models for each climate variable (Meehl et al. 2009; Taylor et al. 2012). This prioritization of emission scenarios by the IPCC reflects a subjective assessment of the estimated likelihood of projected socioeconomic development and potential mitigation measures (Rogelj et al. 2012), and as such may limit the range of uncertainty illustrated because of emission scenario used.

Global climate model response to a specific emissions scenario, or ‘structural’ uncertainty, arises from an incomplete understanding of the climate system and the response of particular climate variables to greenhouse gas forcing. This uncertainty is reflected in the spread across different climate models in their projected sensitivity of the climate to greenhouse gas forcing. Some researchers suggest this type of uncertainty, particularly for global average temperature, is becoming smaller as modeling centers evaluate and improve their model components (Knutti and Hegerl, 2008; Knutti et al. 2013). Nevertheless, at the regional scale and for variables such as precipitation, the magnitude and even the sign of changes varies among models. Since we are using a suite of 6, 7 or 21 climate models, depending on downscaling methods and the choice of climate variable (e.g., precipitation, runoff, streamflow, etc.), model response uncertainty substantially affects our results. Weighting models depending on their performance in simulating the historic, observed climate is one option for resolving this uncertainty. Past performance, however does not necessarily equate with realistic climate sensitivity, and weighted ensemble averaging in practice makes little difference when a large ensemble is used (Mote and Salathé 2010). Given the strong similarities between models developed at the same institution, between models with shared model component versions, and between subsequent model versions, there is not a strong assumption of model independence (Masson and Knutti, 2011). However, results from Gleckler et al. 2008, show that the ‘mean model’, or the model ensemble average from the CMIP3 archive, consistently outperforms all other models in multiple performance metrics. For the PNW,
Rupp et al. (2013) have shown similar results in that there is no one model that consistently outperforms all other models in multiple performance metrics. Thus, we provide results from a relatively large group of models so as to highlight and quantify this uncertainty for the user. Also note that the “extreme” simulations are plausible – ensemble mean only indicates best estimate of central value, not actual year-to-year climate. We provide results representing a range of potential futures in order to enable user selection of the scenario most appropriate for their risk tolerances (users that are highly risk averse might consider the global climate model/emissions scenario combination indicating the earliest emergence, while those that are risk tolerant may consider the combination indicating the latest emergence).

Downscaling may compound model response uncertainty. Statistical downscaling methods are computationally efficient, which allow them to generate output from many models and multiple realizations, but are based on the assumption of statistical stationarity and cannot simulate changes in regional feedbacks. Multiple methods for statistical downscaling are currently in use, with little evidence and less consensus regarding their relative quality. Dynamical downscaling yields higher spatial resolution and can better incorporate regional features and processes, which are important for variables of importance to regional stakeholders, but results are strongly dependent on the lateral boundary conditions and the methods used to constrain the regional climate model to the coarser spatial scale parent global model. Essentially, errors in the global models are retained and potentially amplified by dynamical downscaling (Feser et al. 2011). Global climate model response uncertainty is unlikely to be resolved by the use of downscaled model output in this analysis. For this project, therefore, we have used downscaled climate model output from multiple sources, in order to portray this source of uncertainty. The analytical methods and online delivery mechanisms have been designed to enable ready uptake, analysis and delivery of ToE results derived from additional datasets as they become available.

Uncertainty arising from natural variability is largely inevitable, due to the inherent chaotic nature of spatial and temporal climate variability. Natural variability can create short-term and localized trends that do not correspond to the forced climate response to
greenhouse gas emissions. The dominant modes of natural variability are well recognized, but models vary in their ability to correctly simulate the phase and amplitude of these modes as well as the strength and location of teleconnections (Polade et al. 2013). The ideal way to examine uncertainty from natural variability from climate model simulations, recognizing the limitations of current model ability to simulate such variations, would be to use multiple realizations from each model (Deser et al. 2014). Since internal variability is not coherent across the ensemble while the forced climate response is, the two effects can be distinguished. This approach, however, is beyond the scope of this project. Changes in projected (forced and internal) variability may be analyzed by statistical means. Natural variability contributes to uncertainty in the estimated signal found as a linear fit to the simulated variable, which we do consider. Therefore although uncertainty from natural variability will contribute to the uncertainties indicated by the results, it will not be explicitly resolved at this time.

Uncertainty can also arise from the calculation of ToE itself for a given climate variable. Calculation of ToE requires a number of assumptions, e.g., about (1) the appropriate analytical method (e.g., the “threshold” vs. the “signal:noise” approach), (2) the length of (and data source for) the historical baseline against which ToE will be calculated, (3) the definition of “emergence”, i.e., the threshold of the historical data (for the threshold method) at which “emergence” occurs, and (4) error in the calculation of the signal, i.e., the slope of the linear fit to the simulated data for the threshold method. In this effort, we address these uncertainties by (1) providing results from only the “threshold” method, recognizing that this method is well suited to most of the extreme variables of interest to stakeholders, but acknowledging to the user that other methods might provide slightly different results, (2) providing results derived from ToE calculations using one historical baseline period (1950-1999), but acknowledging to the user that other time periods might provide slightly different results, (3) allowing the user to select the threshold of emergence from a pre-determined suite of options, and (4) allowing the user to select different estimated rates of climate change, within a range spanning the 90% statistical confidence in the calculated rate.

To summarize, we incorporate each of these uncertainties in our ToE analysis as follows:
1) *Uncertainty in future greenhouse gas emissions that force climate change.* This is an inherent uncertainty in what the future will be like in terms of human society. It is dealt with by computing ToE for both a low (SRES_B1/RCP_4.5) and high (SRES_A1B/RCP_8.5) emissions scenario for all variables and datasets.

2) *Uncertainty in the sensitivity of the climate to the projected forcing.* This uncertainty includes both unsettled scientific issues (cloud feedback, ocean heat uptake) and technical difficulties in modeling the climate system computationally. It is dealt with by using an ensemble of climate models that make different, but equally justified, choices in representing the climate. ToE is computed for each model and the range of model agreement establishes a confidence interval for ToE relative to model uncertainty.

3) *Uncertainty in downscaling global climate change projections to the regional scale.* This is another scientifically-unsettled source of uncertainty. We address this by providing results from two statistically-downscaled datasets (BCSD5 and BCSD3) and one dynamically-downscaled dataset (WRF3) and by designing both the analytical methods and online delivery mechanisms to enable efficient incorporation of additional datasets as they become available.

4) *Uncertainty in management sensitivity to climate change.* This is a basic question of how sensitive a particular societal or natural system is to changes in the climate. The answer will vary for different systems depending on their capacity to adapt to change. This uncertainty is incorporated in the ToE calculation through the user-selected level of management sensitivity to change.

5) *Uncertainty in statistically estimating the climate change signal.* The projected future time series of a climate variable (for example temperature) typically includes a steady trend and fluctuations around that trend (both stochastic and cyclic). The steady trend is assumed to be the climate system response to external greenhouse gas forcing and the fluctuations result from the various modes of internal climate variability. Estimating the trend from the time series is a statistical challenge subject to uncertainty. In computing the trend, one can place the true slope within statistical confidence limits depending on the strength of the trend compared to the variance in the data using a Student’s t-test. Thus, ToE can be computed from each model using
a high, central, or low value for the signal based on the confidence interval for the computed trend.

Thus, we have computed ToE many times for each climate variable in order to span each dimension of uncertainty. In the first and fourth cases, higher and lower bounds are selected; in the second case, an ensemble of up to 21 models is used; in the third case, three different input datasets were used; in the fifth case, we use a central estimate with upper and lower bounds. Depending on a user's risk tolerance and perception of uncertainties, either earlier or later Time of Emergence can be obtained by choosing the appropriate combination of these uncertainty ranges across these dimensions. The following selections would result in a high estimate of ToE (i.e., late emergence) for a specific climate variable:

- Selecting a *low emissions scenario* would represent a best-case scenario of low forcing on the climate system and a later ToE as compared to a high-emissions scenario.
- Requiring *high model agreement*, for example, taking ToE as the date where 75% of the models project emergence.
- Applying a *high threshold* for emergence, indicating low sensitivity to change in the variable.
- Using the *lower estimate of the climate trend* would assume the slowest probable rate of climate change.

The web site and visualization tools produced by this project attempt to incorporate all these sources of uncertainty into the results in a way that is intended to match a user's risk perception and allow interactive exploration of uncertainty. Table 11 summarizes how each source of uncertainty is treated in the analysis of ToE, and how each is incorporated into the user experience.
Table 11. Analytical treatment and user experience in the prototype web tool for each component of uncertainty associated with determining Time of Emergence (ToE).

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Analytical Approach</th>
<th>User Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future greenhouse gas emissions</td>
<td>Calculate ToE using projections based on both “High” (RCP8.5 and A1B) and “Low” (RCP4.5 and B1) emissions scenarios</td>
<td>For timelines, summary tables and maps: Allow users to filter ToE results by greenhouse gas scenario</td>
</tr>
</tbody>
</table>
| Climate model disagreement       | Calculate ToE using all global climate model projections available for a particular dataset  
  - 21 GCMs, BCSD5 (temperature, precipitation, streamflow-related variables)  
  - 1 GCM, WRF3 (temperature, precipitation, hydrologic, streamflow-related variables)  
  - 6 GCMs, BCSD3-VIC (temperature, precipitation, hydrologic-related variables)  
  - 7 GCMs, BCSD3-VIC (streamflow-related variables)  
  Flag variables as “non-emergent”?  
  - for spatially-aggregated results from an individual model in cases with disagreement in the direction of the climate change signal among the grid cells in the selected spatial unit showing emergence prior to 2100  
  - for multi-model medians in cases when fewer than 50% of the climate models considered agree on trend direction | In timelines: indicate multi-model median ToE  
In summary tables: report central 50th percentile ToE range  
In summary dot plots:  
  - show individual GCM and multi-model median dates of emergence prior to 2100  
  - indicate direction of the climate change signal associated with each date of emergence  
In maps of Emergence Year: show multi-model median ToE  
In maps of Emergence Location (by year): show locations with 25, 50, 75% model agreement that emergence has occurred |

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7 This table indicates reasons related to climate model uncertainty that variables may be flagged as “non-emergent”. See Table 6 for reasons related to other factors.
<table>
<thead>
<tr>
<th>Downscaling</th>
<th>Calculate ToE using both statistically- (BCSD5 and BCSD3) and dynamically-downscaled (WRF3) datasets</th>
<th>For maps of <em>Emergence Year</em> and <em>Emergence Location</em>: Allow users to filter ToE results by downscaling method (see Table 9) Notify users that the ToE results derived from the dynamically-downscaled dataset (which reflects input from a single global climate model run) are not directly comparable to the results derived from the <em>ensemble</em> of statistically-downscaled global climate models.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural climate variability</td>
<td>For contribution of natural variability to uncertainty in the estimated climate change signal, see “Error in Calculation of Climate Change Signal”, below. Exploration of uncertainty from natural variability in climate model simulations is not explored at this time.</td>
<td>Alert users (in online documentation) to this source of currently unexplored uncertainty.</td>
</tr>
<tr>
<td>Method for calculating ToE</td>
<td>Calculate ToE using only the <em>Signal Threshold</em> method (e.g., Maraun 2013), due to the clarity of communicating the management implications of the relevant computational parameters (i.e., the emergence threshold) and the robustness of the method for a wide variety of climate variables (see Section 2.4, above).</td>
<td>Notify users in online documentation that, although well suited to most of the extreme variables of interest to stakeholders, other computational methods might provide slightly different results.</td>
</tr>
<tr>
<td>Management sensitivity to (or tolerance for) climate fluctuations</td>
<td>Calculate ToE using two definitions of management sensitivity: “High” (negative impacts triggered by the most extreme 20% high/20% low conditions during the 1950-1999 reference period) and “Low” (negative impacts triggered by the most extreme 5% high/5% low conditions).</td>
<td>For timelines, summary tables and maps: Allow users to filter ToE results by management sensitivity In summary dot plots: Show effects of two levels of management sensitivity for ToE results</td>
</tr>
<tr>
<td>Historical baseline to which fluctuations are compared</td>
<td>Calculate ToE using only the 1950-1999 historical reference period.</td>
<td>Notify users in online documentation that alternative definitions of historical reference period could affect ToE results</td>
</tr>
<tr>
<td>Error in calculation of climate change signal</td>
<td>Calculate ToE using three values for the estimated rate of climate change (i.e., the slope of the simulated climate change signal) – the central estimate</td>
<td>For timelines and summary tables: Allow users to filter ToE results by estimated high/medium/low rate of climate change</td>
</tr>
</tbody>
</table>
and “low” and “high” estimates defining the 90% confidence range (i.e., there is a 5% chance the slope is above the faster rate and a 5% chance it is below the slower rate)

| In summary dot plots: Show effects of different assumptions about rate of climate change for ToE results |
|---|---|
5 Project Outputs

The following are outputs of the Time of Emergence project described here.

1. **Project report**, detailing project input and output datasets, methodology for calculating and visualizing Time of Emergence, approach to stakeholder engagement, and the user interface/navigation and technical specifications of the prototype Time of Emergence website.

2. **Results database.** As indicated in Figure 1, development of ToE results for online delivery is a multi-step process resulting in a series of intermediary results datasets. In addition to the results delivered through the prototype web tool, the following intermediary datasets have been archived at the University of Washington.
   a. Time series of variables used in ToE analysis: annual/monthly timeseries for historical and two future scenarios for each grid cell (netcdf) or discrete point (ascii)
   b. Year of emergence for each variable/parameter combination: gridded (netcdf) or station (ascii) date of emergence showing 12 values for each global climate model (2 emission scenarios x 2 levels of management sensitivity x 3 estimates of climate change rate) and 36 values for each ensemble of global climate models (2 emission scenarios x 2 levels of management sensitivity x 3 estimates of climate change rate x 3 levels of model agreement)
   c. Spatially aggregated ToE results: ToE for each variable and spatial unit (119 counties, 218 4th-level (8-digit) HUCs, ~100 stream locations), with 12 values for each global climate model (2 emission scenarios x 2 levels of management sensitivity x 3 estimates of climate change rate) and 36 values for each ensemble of global climate models (2 emission scenarios x 2 levels of management sensitivity x 3 estimates of climate change rate x 3 levels of model agreement)
3. **Maps library.**
   a. Gridded maps of emergence year and emergence location for 127 variables with 20 maps for each variable, for 3 datasets\(^8\), for 2 extents (PNW and Puget Sound) and with 4 boundary overlays (32400 maps total).
   b. Maps of emergence year and emergence location for 30 variables at ~ 100 river locations for 2 datasets, with 20 maps for each variable, for 2 extents (PNW and Puget Sound) and with 4 boundary overlays (9600 maps total).

4. **Prototype web tool.** As described above, the Time of Emergence Prototype website provides the capability to query, retrieve and extract ToE results.

5. **User guide.** A brief manual designed to help the user navigate the prototype Time of Emergence website, conduct customized queries of ToE results, and use the outputs meaningfully.

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\(^8\) Not all variables are mapped for all datasets.
6 Data Archival and Access

All datasets will be preserved and archived at the University of Washington in perpetuity. We expect other organizations, USACE in particular, will mirror these archives to further assure data protection. The Climate Impacts Group has access to a variety of data archive facilities at the University of Washington including local storage on RAID servers maintained by the Department of Atmospheric Sciences, which are accessible over the internet to research collaborators. The local RAID servers will be used for data distribution and for active data analysis. The UW maintains a central archive system (lolo) https://depts.washington.edu/uwtscat/archivestorage where we will archive data products. All data stored to the archive system are duplicated to tape at two separate backup centers in the Seattle area. Archiving to this system will ensure the long-term preservation of project results. Access to archived datasets will be provided upon request to ToE PIs Amy Snover (aksnover@uw.edu) and Eric Salathé (salathe@uw.edu).
7 Moving Forward

Several potential avenues of improvement or expansion of the prototype online tool and underlying analyses developed through the Time of Emergence project may be useful to consider. In this section we describe potential pathways for expanding and improving the tool, specifically: incorporating more input datasets, computing ToE for additional locally-specific, management-relevant variables, expanding the geographic domain covered by the ToE approach, enhancing visualization and online delivery of ToE results, developing a more fully-interactive ToE analytical environment, and evaluating use and application of the prototype ToE tool and underlying results.

For future analysis we would like to include additional statistically and dynamically downscaled model output, which would offer the means to examine climate change across the PNW at fine spatial scales (1/8th degree resolution or less) needed for climate change decision support in management-relevant measures of the climate and environment for the PNW. The Multivariate Adaptive Constructed Analogs (MACA) statistically downscaled climate model dataset has exhibited greater skill in reproducing the spatial and temporal variability of PNW climate, when compared to observations for the 20th century (Abatzoglou and Brown 2012). MACA is derived from the Coupled Model Intercomparison Project phase 5 (CMIP5), is available at a daily time-step and a higher spatial resolution (~6km) than that of the BCSD datasets and has only recently become available. While data management/storage has been an issue throughout this analysis, we recently received +20 TB of space on the Amazon Web Server, which can potentially speed up the pace with which variables and ToE for each variable is calculated. Adding the MACA dataset to our analysis would be straightforward and would greatly enhance the web tool’s ability to compare results across datasets.

Also, the Weather and Research Forecasting model (WRF) has been run with forcings from various CMIP3 and CMIP5 models. At present we have incorporated ToE results from one WRF simulation; additional existing simulations would be straightforward to incorporate into the ToE analysis and online tool, establishing a larger regional climate model ensemble.
One shortcoming of the present analysis is its dependence on BCSD-derived datasets, which use monthly climate model output and therefore may not accurately represent future extreme events. The MACA and WRF downscaling approaches are more suited to daily and shorter time scales, and WRF in particular can represent fine-scale feedbacks in the climate system that can amplify extreme events. ToE analysis and delivery of results would be strengthened by ongoing incorporation of improved regional climate information derived from downscaling approaches like MACA and WRF, especially for extreme events.

As additional projections of PNW climate change become available, or additional user needs identified, ToE could be computed for additional management-relevant variables. One of the most widely requested variables for which the necessary input data do not exist is stream temperature. Multiple research groups are currently working to project future changes in stream temperature under climate change – if these efforts produce timeseries of stream temperature suitable for ToE analysis, this gap could be filled. Many stakeholders also requested ToE information about projected changes in wind and lightning, which could now be developed using projections for management-relevant changes in PNW wind and lightning generated within the past six months using WRF.

There is also potential to expand the present geographical domain from the current focus on the Puget Sound basin and PNW to cover the western United States or even the entire coterminous US. The BCSD datasets used in this study cover these broader areas (western US for BCSD3; coterminous US for BCSD5) as does MACA (coterminous US), and a further-reaching spatial analysis would simply utilize the existing code from the established methodology. This would result in a larger set of spatial units (e.g., more counties and HUCS) to which to compare the existing results.

The number of stream gauge stations used in this study could also be expanded. Of the 297 stream locations in the BCSD-CMIP3, we have analyzed only ~50. Additional
stream locations would enhance future analysis and would not require additional ToE code development.

While the prototype online ToE tool is designed to provide useful and useable information for both novice and sophisticated users of climate change information, additional tool development, such as described in Section 3.3.2, could improve uptake of ToE information by enhancing the user experience and providing additional support for interpretation and application of results. Near-term needs are to identify the most resonant and accessible terminology for describing the management-specific component of emergence (“management sensitivity” on the current site), continue to enhance site navigability, support users of the prototype tool as they develop a deeper understanding of the range and diversity of plausible change in management-relevant climate variables, and migrate the prototype site from the testing server. Additional effort could seek user input to identify what additional information (about the magnitude of emergence thresholds or projected changes, for example) is most needed to support interpretation and application of results. What support do users with different levels of technical expertise need for effectively navigating the site and evaluating the implications of ToE results for their specific decision context? What kinds of adjacent visual comparisons of ToE results based on different analytical assumptions would be most useful to users? Future development could add capabilities for users to comment on specific visualizations, or to save jobs for future viewing. Knowing that these may be of interest, we built “breadcrumbs” tracking user navigation and choices into the prototype site, so as to enable easy establishment of the functionality for saving jobs in the future.

The ToE analysis and online delivery described here used a pre-determined set of values for the analytical parameters necessary for ToE computation (management sensitivity, historical reference period, level of statistical certainty in the computation of the climate change signal). While users can explore how these pre-determined values affect the date of expected emergence, users cannot currently explore ToE for additional parameter values of interest. Future work could expand the set of analytical parameters used in the ToE analysis or apply these methods for ToE computation to develop a fully-dynamic
online application for exploring ToE for any user-specified parameter value, or for user-specified thresholds for threshold-based variables. Further tool development could involve the development of scripts to enable automated ToE analysis of user-provided (correctly formatted) input datasets.

As the prototype online tool is increasingly tested within both USACE and EPA and the broader PNW climate user community, formal evaluation of user experience, tool navigability and understandability, and applicability of ToE results in management and planning contexts could provide valuable insights for prioritizing such future development efforts.
8 Conclusion

Despite the wealth of downscaled climate change projections for the PNW, potential users of this information still struggle to find information about projected changes in environmental conditions of relevance to their particular management concerns, navigate the technical challenges of extracting relevant information from the massive datasets available from climate data providers, and interpret the plethora of available scenarios. In the ToE project, we have reduced the burden for regional practitioners to access and interpret climate change projections by

1. downloading and formatting downscaled model output,
2. using these projections to compute locally-specific, management-relevant variables,
3. evaluating the ToE for these variables under a range of plausible assumptions about future climate and management sensitivity to change,
4. developing syntheses of these results to indicate agreement across numerous global climate models, and for particular locations and levels of agreement,
5. producing a library of maps indicating spatial variability in both ToE and model agreement, and
6. developing a prototype online tool for exploring and accessing these results, in order to provide both novice and sophisticated users relatively easy entry into these complex and numerous datasets.

By accurately representing the variability and uncertainty in projecting future climate, the prototype online tool enables user selection of the scenarios best fitting their decision context and risk tolerance. Combined with information about relevant response times, these results can be used to identify priority areas for more detailed analysis to support climate risk reduction. The flexible method of analysis, visualization and data delivery can be efficiently applied to new data sets as they emerge or are updated.
9 References


