Technical Guidance: Quantifying Climate Change Impacts

THE UW CLIMATE IMPACTS GROUP

Technical Guidance: Quantifying Climate Change Impacts

THIS 18-PAGE COMPANION DOCUMENT IS WRITTEN FOR STAKEHOLDERS AND MANAGERS INTERESTED IN QUANTIFYING SENSITIVITY AND EXPOSURE TO CLIMATE CHANGE.

This guide will help answer the questions...

1. *How do I quantify sensitivity?*
2. *How do I quantify exposure?*
3. *How do I manage uncertainty?*
4. *Where can I find the latest data?*
5. *What do I need to consider when seeking new data?*

1. How do I quantify sensitivity?

The first step in any climate assessment should be to consider the anticipated consequences – whether physical, economic, ecological, cultural, etc. – of climate change. Another way of looking at this is to ask: ***"How much would the climate have to change to matter?"*** or ***"How do impacts scale with the anticipated changes?"***

This may be easy to intuit in some cases (e.g., water overtopping a levee) and more difficult to quantify in others (e.g., consequences for businesses when transportation is disrupted). In either case, the *sensitivity* to climate change is key to understanding the timing and severity of climate change impacts.

An approachable way to quantify sensitivity is to determine *when* the impacts will become a problem. Once you know this, you can then assess *how often* the impact will cause problems, and by *how much*. We suggest approaching this in one of two ways:

Approach #1: Observations

Historically, we have experienced climate impacts resulting from natural variations in climate – warm winters, dry years, big storms, etc. – that vary on time scales from days to several decades. When past events can be related to projected trends due to climate change, the consequences of those events can paint a picture of the potential impacts of climate change.

Approach #2: Modeling

The alternative to the observational approach is to use models to estimate the consequences of projected changes in climate. In a recent study, for example, the City of Portland used an existing stormwater model, testing varying precipitation intensities to see how consequences scale with changes in precipitation.

What if you aren't sure at which point an impact becomes a problem for your community? There are lots of reasons it might be hard to identify a time frame when impacts become important. Knowing exactly when an impact becomes a problem could help prioritize resilience-building efforts, but it isn't the most important part of this step. Instead, the most important thing to understand is which impacts will affect your community the most, so that you can focus on reducing those risks as much as possible.

Once you gather information about the sensitivity of your community, you have much needed context for the next step: quantifying exposure. In short, you now have an idea of how the impacts you experience will be affected by climate change. Next, you'll need to quantify how much change is likely to occur.

2. How do I quantify Exposure?

The three different approaches that are briefly discussed in the accompanying *Introduction to Adaptation* guidance document include (1) using global climate model data, (2) "downscaling" global climate model data, and (3) using impacts model data. You will need to consider the strengths and weaknesses of each approach to decide which path to pursue. Use the flowchart (Figure 1) as a reference for deciding among the different approaches for quantifying exposure.

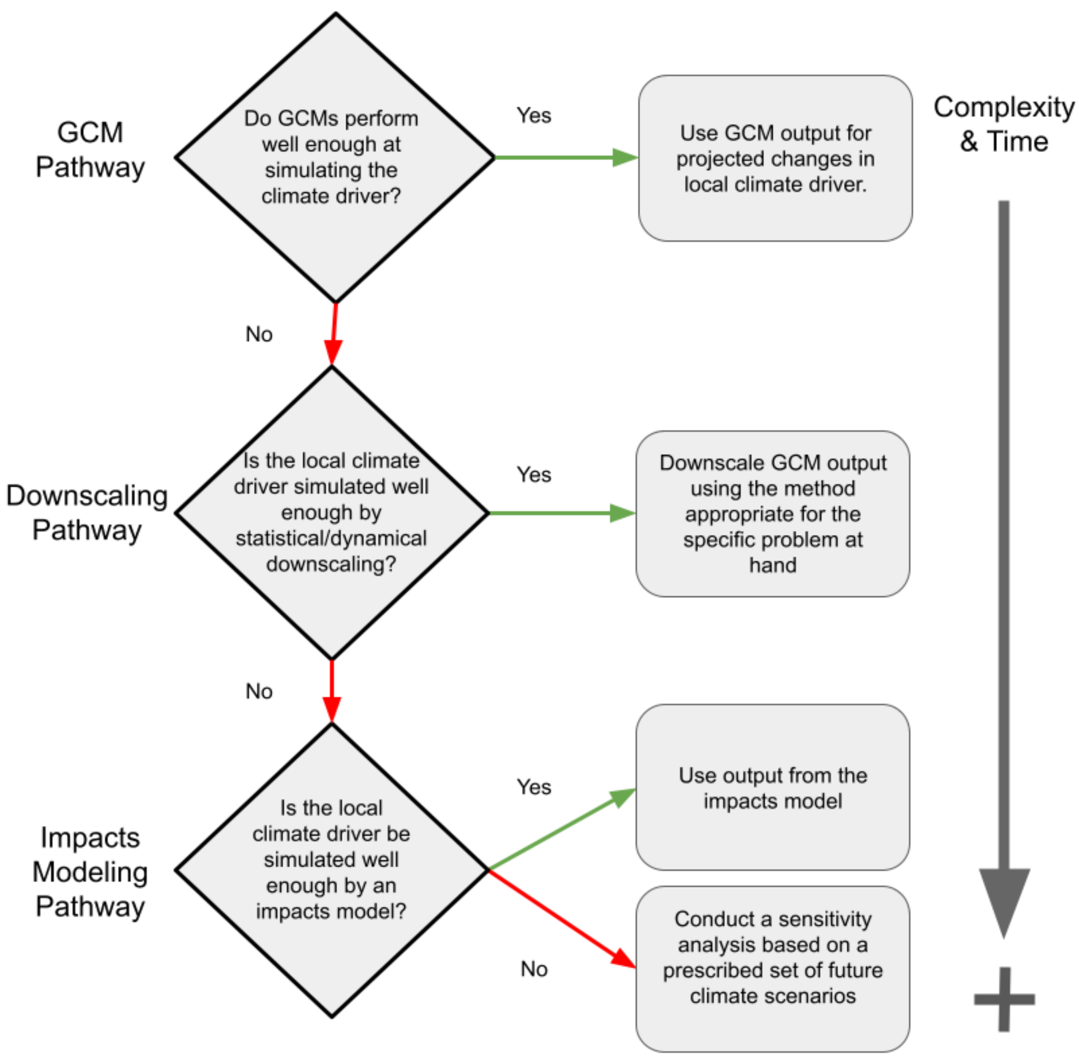

Figure 1. *Flowchart for selecting which data are needed to quantify exposure to climate impacts.*

Global Climate Model Pathway

Global climate models (GCMs) project future changes in a variety of climate variables, including temperature, precipitation, wind, humidity, and many others.

Global climate model output needs to be carefully evaluated to determine the fidelity of each model to observed conditions. Many studies have evaluated climate models by comparing historical climate simulations and observational data for various regions, including the Pacific Northwest (e.g., Rupp et al. 2013). No climate model is perfect, GCMs perform differently depending on which metric you consider. Since there is rarely a "best" model for any purpose, we recommend selecting a subset of GCMs by a process of elimination: removing those that perform poorly with respect to your key metrics of interest.

Another consideration is the scale of the climate impacts of concern for your community. The resolution of global climate models is coarse, with typically about 50-100 miles between grid points. In many situations this can be sufficient. For example, storms and heat waves are controlled by large-scale weather processes that are generally well-captured by GCMs. On the other hand, GCMs can rarely capture the detailed changes associated with these weather events – they are unable, for example, to reproduce the east-west contrast in temperature across Washington State. For the same reasons, GCMs generally do not provide accurate estimates of precipitation (e.g., Salathé et al., 2010).

While GCMs have several disadvantages, they may be sufficient for quantifying exposure in some cases. For example, as a first estimate of projected changes in temperature. Seasonal averaged temperature, in particular, is likely to be well-represented by GCMs.

GCM Pathway Advantages	GCM Pathway Disadvantages
• GCM projections are readily accessible online, for several different greenhouse gas scenarios. • Less time-consuming to gather and analyze GCM data. • Many different GCMs to choose from.	• GCMs have coarse resolution and are not well-suited for determining changes on small spatial scales. • Some quantities, such as precipitation, are not simulated well by GCMs. • GCMs generally do not simulate impacts directly (e.g., changes in streamflow).

When you need to consider finer-scale changes, a different approach may be needed. In these cases, you can use a separate modeling step to translate the coarse-scale GCM projections to the local scales needed to capture microclimates arising due to topography and other factors. This step is often referred to as "downscaling" because it involves going from the coarse-scale GCM projections to finer-scale projections.

Downscaling Pathway

GCMs do not resolve many landscape-scale features that drive impacts. This is the case for heavy rain events, for example, where GCMs are not able to capture important differences such as the intensification of rainfall on windward slopes and rain shadows in the lee of topography. If GCMs do not resolve the local-scale changes you are interested in, then you'll need to consider using downscaled data. There are two approaches to downscaling climate data: statistical and dynamical.

Statistical Downscaling

Statistical downscaling uses empirical relationships to estimate climate impacts on a finer scale. This method of downscaling is easy to implement but doesn't capture any processes that global climate models don't already reproduce. For example, GCMs generally underestimate the additional warming expected east of the Cascades relative to western Washington, and statistical downscaling approaches are not generally equipped to fix this problem.

How changes manifest across the landscape can be important for estimating future impacts. As an example, flooding might change differently if the spatial pattern of rainfall is not the same in the future. Similarly, areas that are currently snow covered but will be snow free in the future will experience additional warming when the ground, because it is much darker than snow, absorbs more sunlight. Statistical downscaling of GCM data will not be able to capture changes like these. More generally, statistical downscaling cannot capture changes in processes, especially when they are outside of the range of past experience.

Dynamical Downscaling

Conversely, the dynamical approach to downscaling uses regional climate models (RCMs). RCMs simulate physical processes in the same way as GCMs, but at finer scales. Because they work at finer scales, RCMs can capture processes that GCMs cannot (e.g., rain shadows and cold air outbreaks). While dynamical downscaling can better capture key processes, it is not necessarily more accurate in every instance, and it is also costly to implement if you need to create your own downscaled dataset.

Which downscaling method do I use?

The answer to this question depends on what you are trying to quantify, and what level of precision you need. Statistical downscaling will capture changes at the spatial resolution of GCMs and is best suited for assessing changes in monthly to annual climate. Statistically downscaled datasets are also more available and much less expensive to produce. However, if the changes are based on processes that are not well represented by GCMs or are outside of the realm of past experience (e.g., rainfall patterns, going from snow-covered to snow-free) then dynamically downscaled projections might be necessary. Further discussion with technical experts can help you understand which option is best for you.

Statistical Downscaling Advantages	Dynamical Downscaling Advantages
• Less time-consuming to produce • Relatively easy to implement on large-scale data	• Better representation of extreme events and microclimates • Greater consistency among weather variables: temperature, humidity, precipitation, wind, radiation, etc. • Captures processes that are outside of the range of past experience

In some cases, neither statistically downscaled nor dynamically downscaled projections may provide the information you need to quantify exposure. As with GCMs, downscaled projections provide estimated changes in climate variables: temperature, precipitation, and sometimes also wind, humidity and radiation. But the impacts of interest to you may be related to variables that are not readily available from GCMs or downscaling (e.g., streamflow). In these cases you can use output from an impacts model to gather the exposure information you need.

Impacts Modeling Pathway

A hydrologic model is an example of an impacts model – it can be used to assess changes in streamflow, snowpack, soil moisture, and other aspects of the water balance. Here we will focus on hydrologic models because of their utility for the Floodplains by Design project, but it is worth noting that other impacts models, such as vegetation and wildfire models, could be more appropriate in certain instances.

Hydrologic Models

Hydrologic models track the water budget by determining how much water is stored in soils and snowpack, how much goes to runoff, and how each changes in response to precipitation, evapotranspiration, and snowmelt. Most hydrologic projections for the Pacific Northwest have used either the Variable Infiltration Capacity macroscale hydrologic model (VIC; Liang et al. 1994, Liang et al. 1996, Gao et al. 2010) or the Distributed Hydrology Soil Vegetation Model (DHSVM; Wigmosta et al., 1994; 2002). Other models such as PRMS (Markstrom et al. 2015, Regan & LaFontaine 2017, Regan et al. 2018), VELMA (Abdelnour et al. 2011, Mckane 2014), and RHESSys (Tague & Band 2004) have particular advantages, and are beginning to be used more frequently for climate assessments in the Pacific Northwest.

Hydrologic Model Advantages	Hydrologic Model Disadvantages
• Direct simulations of streamflow for the desired region • Takes into consideration many factors that impact streamflow (e.g., groundwater, evaporation, runoff, and snow)	• Necessary to have downscaled climate data prior to running a hydrologic model • Hydrologic modeling can be time-consuming and expensive

3. How Do I Manage Uncertainty?

All approaches to quantifying sensitivity and exposure include uncertainty. For sensitivity, you may not have been able to quantify exactly when an impact will become a problem for your community, or just how large the consequences of an impact will be. This is partly why we recommend assessing sensitivity iteratively. Continuously refining and considering which impacts your community is most sensitive to through use of both observations and modeling will help you adaptively manage in response to this uncertainty.

For quantifying exposure, uncertainties in model projections can be broken down into three categories:

1. ***How much greenhouse gases we will emit in the future.*** We cannot predict the future of human behavior. To assess uncertainty in future emissions, climate projections are developed for multiple greenhouse gas scenarios that provide plausible storylines of future emissions.

2. ***The timing and magnitude of natural variations.*** Weather and climate will continue to fluctuate in the future, which can temporarily enhance or obscure climate change trends. To avoid confusing random variations with climate-related trends, a common practice is to assess changes over 30-year periods or longer.

3. ***Limitations in our modeling of key processes.*** No model is perfect: models can be limited in accuracy, or they can omit key processes altogether. The best approach is to carefully validate models using observations, and to develop projections based on different models or modeling assumptions.

Although models will improve over time, some of this uncertainty is irreducible: there will always be uncertainty in climate projections.

Choosing Global Climate Models

All models do not perform equally well. Because of this, every generation of GCMs undergoes thorough performance evaluations. Evidence from these performance evaluations shows that there are no "best" models that outperform others across the board (Brekke et al. 2008). The same research indicates that the best approach is to use an "ensemble" of GCMs – we recommend using 6-10 GCMs per climate projection scenario to accurately represent the average and the range among projections. For the Pacific Northwest, the most recent model evaluation is Rupp et al. (2013).

Choosing Greenhouse Gas Scenarios

Though there is a large spread in possible greenhouse emissions, there is little difference in temperature change across emissions scenarios until 2050. As a result, if you only need to consider changes up to mid-century it will suffice to only use one scenario. If you need to consider changes past 2050, the choice of greenhouse gas scenario matters. You may decide to manage risk by developing a strategy that is robust to many conditions. In this case you would want to consider at least a high and a low scenario for comparison (Snover et al. 2013).

New GCM Projections: "CMIP6"

The most recent iteration of global climate model projections is a result of the Coupled Model Intercomparison Project – Phase 6 (CMIP6). In the CMIP6 model simulations, the different greenhouse gas scenarios are referred to as "shared socioeconomic pathways", or SSPs. The first number after each SSP indicates what kind of future narrative the SSP includes (i.e., how difficult climate change mitigation and adaptation will be), with larger numbers generally indicating more difficulty for mitigation and adaptation. The final two numbers indicate the amount of climate forcing by 2100 or, in other words, how strong of a warming effect the greenhouse gases will have. In general, the larger the final two numbers the more greenhouse gas emissions in the scenario and therefore the more warming the world experiences by the end of the century.

Figure 2 shows the projected rates of climate forcing for each SSP, along with the projected rates of climate forcing for

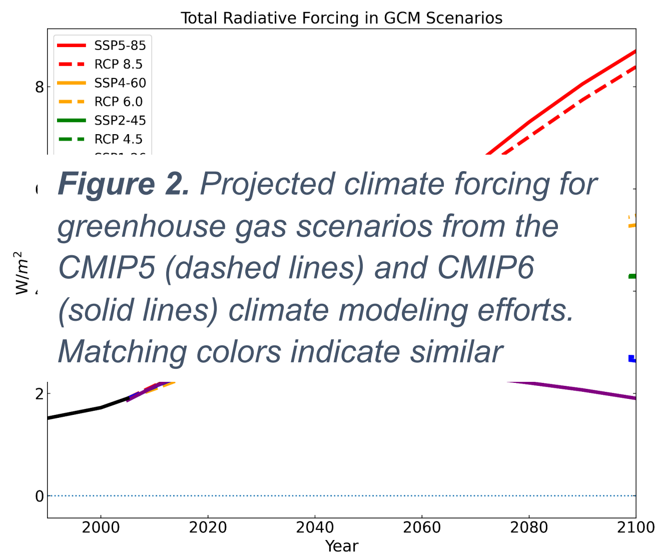

Figure 2. *Projected climate forcing for greenhouse gas scenarios from the CMIP5 (dashed lines) and CMIP6 (solid lines) climate modeling efforts. Matching colors indicate similar*

the greenhouse gas scenarios from the previous GCM effort iteration (CMIP5). These previous scenarios are termed "representative concentration pathways" (RCPs). Many existing studies rely on CMIP5 data, so much of the data you will consider leveraging for quantifying sensitivity and exposure will be based on these older scenarios. SSPs and RCPs, despite being from different GCM generations, are comparable. For example, the RCP 4.5 scenario has nearly identical climate forcing SSP2-45 (green lines in Figure 2).

When looking past 2050, many decision-makers use RCP 4.5 (the low greenhouse gas scenario) and RCP 8.5 (the high greenhouse gas scenario) to bracket the range of possible future climates. Moving forward into the next generation of scenarios, this will likely be replaced with SSP2-45 and SSP5-85.

4. Where can I find the latest data?

Raw global climate model output can be downloaded from the World Climate Research Programme's (WCRP) website. The WCRP website provides access to several different generations of climate model data, however this data is not always straightforward to access, nor is it in a format that is user-friendly.

A more approachable way of accessing available global climate data is this Tableau visualization, which provides an overview of changes in temperature and precipitation for the Pacific Northwest in three generations of global climate model project.

For additional resources on available climate model data visualizations, raw downscaled climate models data, coarse-scale hydrologic projection output, and fine-scale DHSVM output see tables 1-4.

5. What do I need to consider when seeking new data on sensitivity and exposure?

The first things to consider are the costs and benefits of conducting new modeling or obtaining new observations. Finding or creating new datasets is expensive and time-consuming, and it may not be worth the effort for the information it provides. In many instances, you will be able to leverage existing data for quantifying sensitivity and exposure.

Should existing data be insufficient for your needs, the following considerations may be important when seeking new data.

1. ***Do I need new observations or modeling?***

   Obtaining new observations can often be more time-consuming and expensive than modeling, especially when considering that multiple years of observations may be needed to draw accurate conclusions.

It is important to consider, however, that model simulations require observations for validation. If you are unable to find observations in your region that will allow you to validate model simulations, then obtaining new observational data should be a priority. Modeling may be needed in addition to observational data if the changes you are interested in cannot be measured directly, or if the changes in the future go beyond the range of what has been seen in the past.

2. ***If I need modeling, what sort of impact model should I use?***

   Answering this question depends on the impact you are concerned about, and will require conversations about project constraints (e.g., time, funds, etc.) with those providing technical guidance. Additionally, many previous impacts modeling efforts have their data publicly available (e.g., see tables below). It's worth making sure you cannot leverage any existing publicly available data before deciding on this pathway.

3. ***If I plan to use GCMs, what future greenhouse gas scenarios should I use?***

   In general, the two scenarios we recommend that encompass a range of likely greenhouse gas emissions are the low emission scenario, RCP 4.5, and the high emission scenario, RCP 8.5. As noted above, the temperature projections for RCP 4.5 and RCP 8.5 are similar prior to around 2050. If you're only concerned with changes through the year 2050, this means that you can use just one future greenhouse gas scenario. If you are considering risks after the year 2050, you may want to include both scenarios in your assessment. As more model data becomes available and is analyzed, these two scenarios will likely be replaced with SSP2-45 and SSP5-85, which are equivalent to RCP 4.5 and RCP 8.5 in their climate forcing by the end of the century.

4. ***Different ways of quantifying our impact of concern do not agree. What next?***

   This could be a sign of an error in one of the datasets or models you are using. As a starting point, we suggest reviewing the methods used in each approach, and double-checking your calculations. It is possible that specific assumptions used in one approach but not another may have a large effect on the results.

   If you are relying on model results, check to see how historical model results compare to observations – one may outperform others, suggesting that it could be more reliable for assessing future changes. If possible, consider how the model reproduces the sensitivity to climate change, for example by comparing conditions in warm vs cold years. Finally, it is possible that the impacts you are hoping to consider are simply difficult to model accurately. In this case you will need to develop plans that are adapted to a high degree of uncertainty.

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Available Climate Model Data Resources

Table 1. A partial summary of available online tools to explore projected conditions in the Pacific Northwest

Tool	Description	URL
Climate Toolbox	A collection of web tools for visualizing past and projected climate and hydrology of the contiguous United States.	https://climatetoolbox.org/
U.S. Climate Resilience Toolkit	A collection of web tools, information, guidance, and case studies on building climate resilience in the United States.	https://toolkit.climate.gov/
Pacific Northwest Climate Projection Tool	A tool that shows the projected changes in annual and seasonal temperature and precipitation for the Pacific Northwest and the globe, comparing multiple generations of Global Climate Models.	https://cig.uw.edu/resources/analysis-tools/pacific-northwest-climate-projection-tool/
Interactive Sea Level Rise Data Visualizations	Two interactive visualizations that allow users to compare sea level rise projections out to the year 2150.	https://cig.uw.edu/our-work/applied-research/wcrp/sea-level-rise-data-visualization/
Heavy Precipitation Projections for use in Stormwater Planning	A web tool that allows users to visualize projected changes in heavy rainfall events across the Pacific Northwest as a function of decade, duration, and return interval (frequency).	https://cig.uw.edu/resources/analysis-tools/

Tribal Climate Tool	A web tool to aid tribes in the Pacific Northwest understand how the climate is projected to change in the places they care about, providing maps, graphs, tables, and descriptions.	https://climate.northwestknowledge.net/NWTOOLBOX/tribalProjections.php

Available Downscaled Climate Model Data

Table 2. A partial summary of available downscaled climate model datasets for the Pacific Northwest

Method	Type	Citation	URL
Multivariate Adaptive Constructed Analogs	Statistical	Abatzoglou & Brown, 2012	http://www.climatologylab.org/maca.html
Localized Constructive Analogs	Statistical	Pierce, D. W., D. R. Cayan, and B. L. Thrasher, 2014	http://loca.ucsd.edu/

WRF 12km	Dynamical	Salathé et al., 2010	https://cig.uw.edu/datasets/dynamically-downscaled-hydroclimate-projections-wrf-model/

Summary of Coarse-Scale Hydrologic Projections

Table 3. A partial summary of available coarse-scale hydrologic datasets projecting changes in streamflow for the Pacific Northwest.

Dataset	Full Name	Citation	URL
HB2860 (RMJOC-I)	PNW Hydroclimate Scenarios Project	Hamlet et al., 2013	http://warm.atmos.washington.edu/2860/

RMJOC-II / CRCC	Hydrologic Response of the Columbia River to Climate Change	Chegwidden et al., 2019	https://hydro.washington.edu/CRCC/
LLNL-Maurer	Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections	Web archive: Maurer et al., 2007; Climate proj.: Reclamation, 2013; BCSD CMIP3: Reclamation, 2011; BCSD CMIP5: Reclamation, 2014	https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/

Summary of Fine-Scale Hydrologic Projections

Table 4. A partial list of available fine-scale streamflow projections for the Pacific Northwest.

Watershed	Contact	Citation	Links
Hood Canal & Eastern Strait of Juan de Fuca	R. Murphy and C. Rossi	Murphy, R. and Rossi, C. (2019)	Project Page

Snohomish	S.-Y. Lee	Lee et al., 2018	Project Page
	G. Mauger	Mauger et al., 2018	Publication Page
Stillaguamish	B. Mitchell (WWU), G. Mauger	Mitchell et al. 2018, 2019	Publication Page
Nooksack	B. Mitchell (WWU), R. Murphy	Dickerson-Lange, 2014	Publication Page