A Practitioner's Guide to Climate Model Scenarios

GLISA
A NOAA RISA TEAM

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ABOUT GLISA

The Great Lakes Integrated Sciences and Assessments (GLISA) is a collaboration between the University of Michigan and Michigan State University and is supported by the National Oceanic and Atmospheric Administration (NOAA). GLISA is part of a network of eleven Regional Integrated Sciences and Assessments (RISA) teams dedicated to helping the nation prepare for and adapt to climate variability and change. GLISA was established in 2010 and serves the eight Great Lakes states and the province of Ontario.

For more information, visit glisa.umich.edu.

RECOMMENDED CITATION

A Practitioner's Guide to Climate Model Scenarios. (2021) Great Lakes Integrated Sciences and Assessments (GLISA). Ann Arbor, MI. Briley, L., Dougherty, R., Wells, K., Hercula, T., Notaro, M., Rood, R., Andresen, J., Marsik, F., Prosperi, A., Jorns, J., Channell, K., Hutchinson, S., Kemp, C., and O. Gates, eds.

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THIS GUIDE IS FOR

This Guide is written for practitioners already using or wanting to use future climate information in their work, but who are not familiar with the underlying assumptions and choices surrounding climate data. Here, we introduce the climate model scenarios that are used to "drive" climate models forward in time. These scenarios are a combination of socioeconomic and climate forcing pathways. We summarize differences between these scenarios for the Great Lakes region to show users how their choice of model scenario affects future temperature and precipitation projections. The examples throughout feature projections for the Great Lakes region, since this is the area GLISA serves, but the main messages and content are applicable to any region or country.

GLOSSARY TERMS

GLISA provides definitions for terms throughout this Guide in the Glossary.

ACKNOWLEDGEMENTS

GLISA would like to thank the following individuals for their contribution to helping ensure this Guide speaks to and meets the needs of practitioners. These individuals are either in GLISA's Stakeholder Working Group (denoted WG) or Scientific Advisory Committee (denoted SAC) for our Great Lakes Ensemble project (http://glisa.umich.edu/projects/great-lakes-ensemble). The WG consists of practitioners from many sectors (e.g., Tribal, natural resources, cities, agriculture, etc.) who are using climate information in their work to inform decision making. Members of the SAC helped to ensure the information in this Guide is scientifically accurate and reliable.

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We would also like to thank Katharine Hayhoe and Rebecca Lindsey who provided their general expertise and feedback to improve the Guide.

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ACRONYMS

BAU	Business as Usual
CMIP	Coupled Model Intercomparison Project
GCM	Global Climate Model/General Circulation Model
GHGs	Greenhouse Gases
GLISA	Great Lakes Integrated Sciences + Assessments
HighRes-MIP	High Resolution Model Intercomparison Project
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
NA-CORDEX	North America Coordinated Regional Downscaling Experiment
RCM	Regional Climate Model
NOAA	National Oceanic and Atmospheric Administration
RCPs	Representative Concentration Pathways
SPAs	Shared Policy Assumptions
SSPs	Shared Socioeconomic Pathways
UW-RegCM4	University of Wisconsin's Regional Climate Model version 4

CONTENTS

A PRACTITIONER'S GUIDE TO CLIMATE MODEL SCENARIOS

This guide covers what practitioners need to know about Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) before choosing, or using, climate projections in their work.

QUICK-STEP GUIDE FOR PRACTITIONERS

Practitioners can use the steps outlined here to make an informed selection of climate projections for their work and gain a better understanding of the type of future they represent.

1. Read this guide to obtain a better understanding of the various modeling considerations that influence the climate projections you plan to use in your work. Described in greater detail within the body of this document, these considerations include the following:
2. **CLIMATE MODEL SELECTION:** Your first step will be to choose the most appropriate climate models based on the quality of information they provide for your region/location. The assumptions made in creating the different climate models may be more appropriate for some locations than for others. If you do not know which climate projections to start with, work with a climate service provider to learn about your options.
3. **SOCIOECONOMIC PATHWAY SELECTION:** Use the Shared Socioeconomic Pathways, or SSPs, descriptions (see SSP Narratives) to decide which (or all) SSPs are most relevant or acceptable for your work - there's no wrong answer!
4. **REPRESENTATIVE CONCENTRATION PATHWAY SELECTION:** Based on the SSPs that you choose in Step 3, determine the corresponding Representative Concentration Pathways, or RCPs (see Figure 3 and Table 1), that projections are based on.
5. Use projections that are based on the RCPs determined in Step 4. If not all RCPs are available for your choice of climate model (and thus projection data), consult our guidance in The Problem of Limited RCPs section.

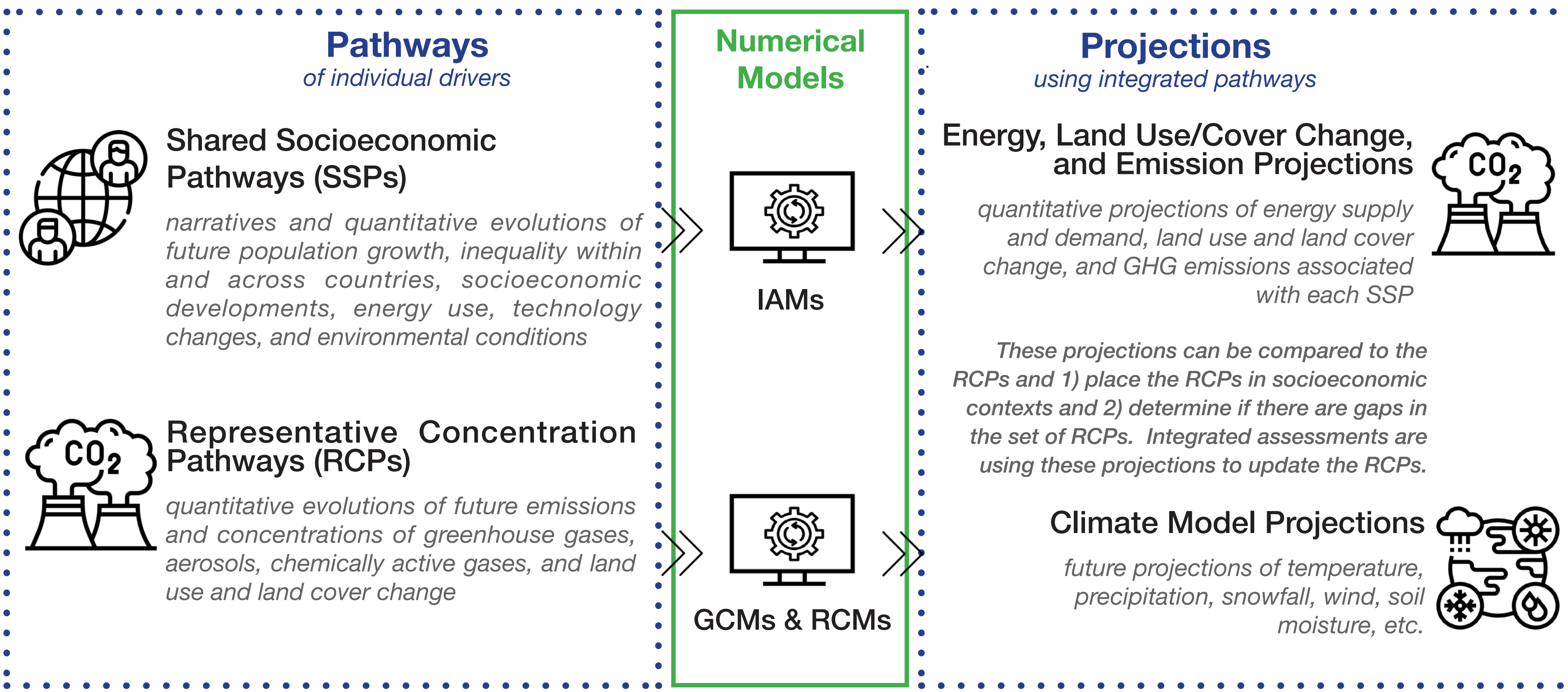
SUMMARY OF PATHWAYS

Climate adaptation practitioners, those working on climate change-related problems, use climate projections to gain a picture of the types of climate challenges they may face in the future. Future projections differ from one another based on the underlying climate model that is used and the scenario that "drives" the model. In this guide we, GLISA, detail these different scenarios to help practitioners better understand what is represented in the climate projections they may use.

The scenarios used in climate modeling are a combination of socioeconomic and climate forcing (i.e., radiative forcing) "pathways". The Shared Socioeconomic Pathways (SSPs) describe how global societies might evolve with respect to population growth, inequality within and across countries, socioeconomic developments, energy use, technology changes, and environmental conditions. Each SSP is translated into future projections of energy, land use/cover change, and greenhouse gas (GHG) emissions, which are inputs to climate models in the form of Representative Concentration Pathways, or RCPs.

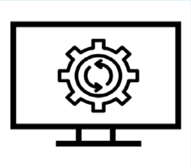
Initially, the two sets of pathways, RCPs and SSPs, were developed simultaneously, or in "parallel." The original set of RCPs (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) used in climate model experiments are not the result of specific SSPs, but rather are "representative" of the range of dozens of pathways published in scientific literature. In Figure 1, the parallel approach is shown where the SSPs are input to Integrated Assessment Models (IAMs) that produce projections of energy, land use/cover change, and GHG emissions, which are comparable to the RCPs. The "parallel" approach was used because it allows for greater flexibility within the IAM and climate modeling community and does not require a new RCP every time a new SSP

Figure 1: *Flow diagram relating Shared Socioeconomic Pathways (SSPs), Representative Concentration Pathways (RCPs), and climate projections and the different models that are used. Integrated Assessment Models (IAMs) are used to simulate SSPs and validate current RCPs as well as to identify opportunities to create new RCPs. The RCPs are used in climate model simulations to produce projections of future climate variables, such as temperature or precipitation. Icons: Flaticon.com*



is generated, and vice versa. This is because climate models only require information about the concentration of GHGs and aerosols emitted by humans and land cover conversion over time and their impact to Earth's radiative balance, regardless of who, how, or where; integrated assessment focuses on these additional socioeconomic details. Another advantage of the parallel approach is that the climate projections practitioners use do not have to be updated every time a new SSP is developed because different SSPs can sometimes be characterized by the same RCPs.

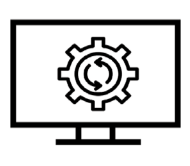
Box 1: Integrated Assessments



Researchers use Integrated Assessment Models (IAMs) to explore interactions between the economy, energy system, land use and land cover change, and the climate system. These assessments, as shown in Figure 1, translate possible socioeconomic futures (i.e., SSPs) into energy, land use/cover change, and emissions projections, which are used as inputs to climate modeling to project future climate changes. IAMs help answer "what if?" questions, such as what if the world takes no action to mitigate climate change, or what if certain energy technologies are not available in the future? There are numerous "what if" questions that could be explored using the pathways, so the climate modeling community decided to initially focus on four pathways that are "representative" of the entire set, which are the RCPs. As the integrated assessment field advances, new RCPs are being considered to fill gaps in the current set.

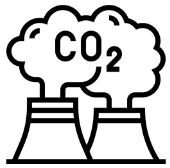
As the science of integrated assessments has advanced, SSPs and RCPs are being more fully integrated in climate modeling. The most recent set of global climate projections in the Coupled Model Intercomparison Project, CMIP6 (Eyring et al. 2016), are associated with a combined SSP and RCP pair of pathways. This helps practitioners to have a better understanding of the specific socioeconomic conditions that a projection is based on. Integrated assessments have also revealed some important findings: the two RCPs with the least amount of climate forcing (RCP2.6 and RCP4.5) are not feasible without some amount of climate mitigation effort. In addition, integrated assessments show the RCP with the most climate forcing (RCP8.5) is only possible under a narrow set of socioeconomic conditions (see Box 3: Understanding RCP8.5). Three new RCPs are being developed to fill these gaps, including RCP7.0, and two new mitigation scenarios, RCP3.4 and an RCP below 2.6. The remainder of this guide provides more details on RCPs and SSPs and further context for RCP8.5, offers practitioners some suggestions for how to choose climate projections for their work, and provides recommendations for how practitioners can choose and utilize climate forcing scenarios.

Box 2: Coupled Model Intercomparison Project (CMIP)



Researchers use CMIP, the Coupled Model Intercomparison Project, a global coordinated effort to standardize global climate model (GCM) experiments and model output, compare and evaluate GCMs, and make GCM data publicly available. "Coupled" refers to the interconnected components of the climate system (i.e., land, air, water, etc.) that are simulated by the climate models, and "intercomparison" references the many models that are available to compare with observations and to one another to characterize model uncertainty and scenario uncertainty. The CMIP project started in 1995 and has multiple versions, including CMIP3 (2005), CMIP5 (2011), and CMIP6 (2018) - there was no CMIP4. Each version of CMIP consists of dozens of climate models from different modeling centers around the globe. As the CMIP project has advanced, so has the scientific information and simulation of important climate processes in the models. CMIP models were not specifically designed to predict future climate changes or provide information for adaptation applications; rather, they are a scientific tool to perform simulated climate experiments. However, these models have gained an audience working in climate adaptation, and CMIP is used to inform high-profile climate reports, such as the IPCC assessments and the U.S. National Climate Assessment (USGCRP, 2018).

REPRESENTATIVE CONCENTRATION PATHWAYS (RCPs)



- Four RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) were created in 2008 in preparation for the IPCC's Fifth Assessment Report.
- RCPs are named for their net amount of climate forcing (W/m^2) at the end of the 21st century. They describe future pathways of emissions and concentrations of GHGs, aerosols, chemically active gases, and land use/cover change.
- The four RCPs are "representative" of dozens that were proposed in research (Figure 2). New RCPs are under development for future use, including RCP7.0 and two new mitigation pathways, RCP3.4 and RCP below 2.6.
- RCPs do not prescribe socioeconomic or policy conditions.
- The RCPs were developed as equally likely pathways, but practitioners may judge some as less achievable than others or some more likely than others based on their socioeconomic descriptions (see Shared Socioeconomic Pathways).
- The choice of RCP matters most after mid-century when climate projections start to diverge due to differences in the pathways (see section: A Great Lakes Regional Perspective). The choice of RCP for mid-century projections, and earlier, is not as important as other factors, such as the underlying climate model(s) used or the role of natural variability.
- Practitioners planning beyond mid-century should base their choice of RCP(s) on the decisions they are trying to make and explore multiple RCPs whenever possible. For example, practitioners whose applications are sensitive to small climate changes (e.g., delicate ecosystems) may find incorporating lower emissions scenarios (e.g., RCP2.6 or RCP4.5) useful to explore those sensitivities. Practitioners needing a "business as usual" scenario may want to explore RCP6.0 or higher, and RCP8.5 offers a high emissions pathway.

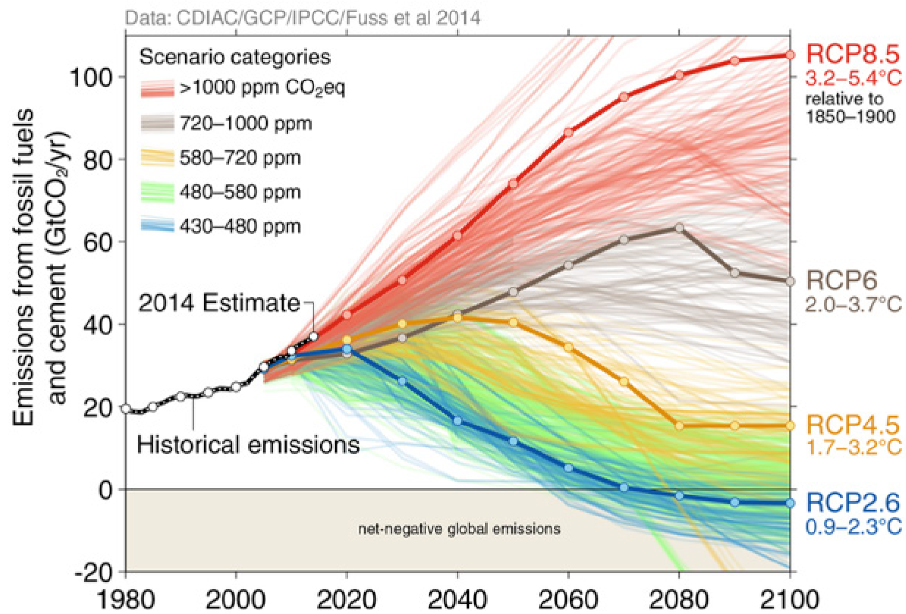
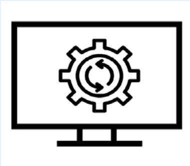


Figure 2: *Global emission trajectories. The thick black line represents historical emissions, pale colored lines represent the dozens of proposed emission pathways produced by the IPCC AR5 Working Group 3, and the thick colored lines represent the four RCP scenarios that were chosen as "representative" of the group. Figure taken from Fuss et al. (2014).*

Box 3: Understanding RCP8.5



RCP8.5 is currently the pathway with the highest amount of GHG emissions. Some practitioners have termed RCP8.5 as either a "business as usual" (BAU) or "worst case" scenario. These labels were not assigned to the RCPs by their developers; rather, they emerged by those using them. However, neither label is necessarily accurate. Each of these claims are explored next. Ultimately, practitioners will need to decide for themselves if they want to accept the underlying assumptions of RCP8.5 (including a possible socioeconomic description of it provided by SSP5) before using it in their planning.

RCP8.5 is a high business as usual (BAU) pathway

RCP8.5 depicts a case of emissions that are high "not only compared to the overall emissions scenario literature, but also compared to the set of baseline scenarios" (Riahi et al. 2011). High emissions are in part due to slow improvements in energy efficiency, which are "well below the historical average" (Riahi et al., 2011). For these reasons, RCP8.5 is a "relatively conservative" (Riahi et al., 2011), or in other words, "high" BAU case with assumptions of low income, high population and high energy demand. In CMIP6, RCP8.5 is combined with SSP5 to create the SSP5-8.5 scenario where baseline carbon dioxide emissions are even higher than in the RCP8.5 pathway (see Figure 3 of O'Neill et al. 2016). RCP7.0 is a new pathway in CMIP6 characterized by carbon dioxide emissions that more closely mirror current trends (see Figure 3 of O'Neill et al. 2016). GLISA recommends using the SSP3-7.0 scenario as an alternative BAU case when less extreme assumptions about the future are desired. If a practitioner is using CMIP5 projections, GLISA recommends exploring RCP6.0 as an alternative to the high RCP8.5 BAU case (additional recommendations on RCP6.0 below).

RCP8.5 is not the absolute "worst case" scenario

Though RCP8.5 has the highest emissions of the four currently available RCPs, it is not the highest pathway from the full suite of proposed emissions scenarios (see Figure 2) nor is it a hard upper bound for what is possible. However, we already established that RCP8.5 is more extreme than current emissions trends.

Alternatives to RCP8.5

Since RCP8.5 is only possible under a narrow set of assumptions outlined in SSP5, and the remaining SSPs converge closer to RCP6.0, GLISA suggests using RCP6.0 or RCP7.0 (once available as part of CMIP6) as an alternative BAU pathway. Unfortunately, projections for RCP6.0 and RCP7.0 are not as widely available compared to RCP8.5. This is because RCP6.0 is not part of the core set of CMIP5 model simulations (modeling groups were only required to submit RCP4.5 and RCP8.5). In CMIP6, SSP5-8.5, SSP3-7.0, SSP2-4.5, and SSP1-2.6 are part of the top tier requested scenarios (O'Neill et al. 2016). In the case that only RCP8.5 is available but other scenarios are desired, refer to GLISA's guidance in "The Problem of Limited RCPs (and what to do about it)."

SHARED SOCIOECONOMIC PATHWAYS (SSPs)

- Five SSPs were developed at the 2007 IPCC Workshop on Scenarios and developed over the following decade.
- SSPs describe possible future population growth, energy use, technology changes, and environmental conditions, among other factors out to 2100. See "SSP Narratives."
- The SSPs span the "challenge space" (Figure 3) of different degrees of mitigation and/or adaptation challenges society could face in the future. Factors that make it difficult to achieve effective climate mitigation include: high rate of unsustainable

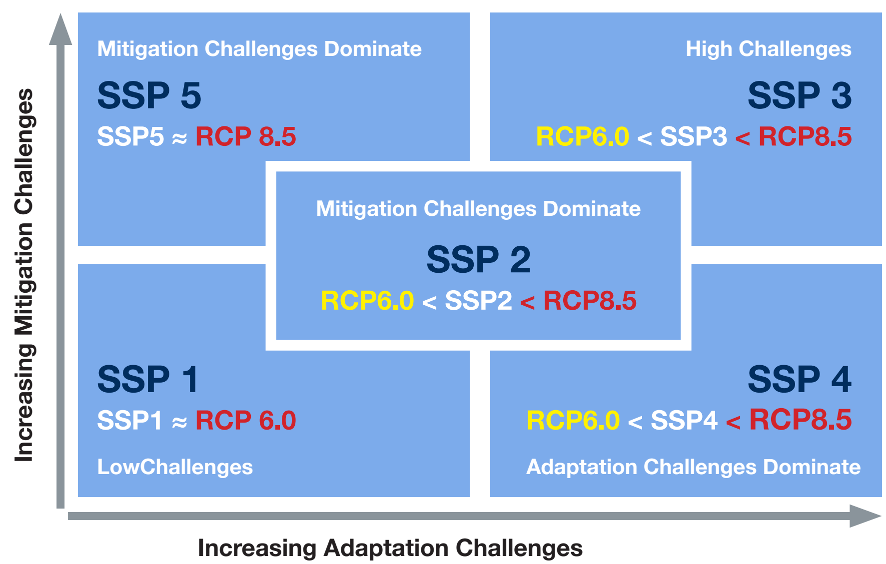


Figure 3: *The SSPs span the range of adaptation and mitigation challenges, each within one of the five "challenge spaces." The corresponding RCP level(s) of each SSP is displayed for comparison. Figure adapted from O'Neill et al. 2014. RCP levels determined using Riahi et al. (2017) Figure 5.*

economic development, technological advancement that is not environmentally friendly, and more reliance on carbon versus other energy sources. Factors that make it difficult for societies to adapt to climate changes include: high population growth, social inequalities, low investments in human capital, regionalized world view, and institutions (e.g., agricultural research and development, forest management organizations, etc.) that are ineffective at promoting climate adaptation/mitigation (O'Neill et al. 2016).

- The SSPs began as a set of narratives, then models were used to elaborate on their economic and demographic components, and lastly IAMs (see Box 1) were used to translate the SSP components into projections of future energy supply and demand, land use and land cover change, and GHG emissions— the same components that make up RCPs and are used in climate modeling. A table comparing the relative growth of these components for each SSPs is provided in Figure 4.
- None of the current SSPs map to RCP4.5 or RCP2.6 without including global mitigation action (Table 1), so practitioners using those pathways must assume mitigation action occurs in the future.
- SSP3 and SSP5 can not achieve climate forcing as low as RCP2.6, even with mitigation actions applied.
- A new, unmitigated RCP7.0 is under development and will bridge the gap between RCP6.0 and RCP8.5 where the baselines for SSP2, SSP3, and SSP4 reside.
- The IAM community is working on "deep" mitigation scenarios to explore the possibility of climate forcing <RCP2.6.

	SSP1 Low Challenges	SSP2 Intermediate Challenges	SSP3 High Challenges	SSP4 Adaptation Challenges Dominate	SSP5 Mitigation Challenges Dominate
RCP 8.5	These SSPs do not reach RCP 8.5				Baseline
			Baseline		
		Baseline		Baseline	
RCP 6	Baseline				Lower RCPs possible with mitigation action
RCP 4.5			Lower RCPs possible with mitigation action		
RCP 3.4		Lower RCPs possible with mitigation action		Lower RCPs possible with mitigation action	
RCP 2.6	Lower RCPs possible with mitigation action		Not possible to achieve RCP2.6		Not possible to achieve RCP2.6
RCP 2.0	Very low climate forcing scenarios to be developed				

Table 1: *The baseline climate forcing levels that each SSP produces are shown. The baselines are presented as a range based on the multiple models that were used to simulate the SSPs and the variability among their outcomes. The baselines are achieved assuming no mitigation action, but they can produce lower levels of climate forcing when mitigation actions are taken (moving down a column). Figure adapted from Riahi et al. (2017) Figure 5 and van Vuuren et al. (2014) Figure 4.*

SSP NARRATIVES

The following narratives were developed to describe the underlying global conditions in each SSP. These descriptions were taken directly from Riahi et al. (2017).

SSP1	**Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)** The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
SSP2	**Middle of the Road (Medium challenges to mitigation and adaptation)** The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements, and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly, and challenges to reducing vulnerability to societal and environmental changes remain.
SSP3	**Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)** A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.
SSP4	**Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)** Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor-intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.
SSP5	**Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)** This world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource- and energy-intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Comparison Chart of SSP Components at 2100

						Source of information
Population Growth	SSP1	SSP5	SSP2	SSP4	SSP3	
Urbanization	SSP1	SSP2	SSP4	SSP1	SSP5	
GDP	SSP3	SSP4	SSP2	SSP1	SSP5	*Figure 2 of Riahi et al. 2017*
Energy Demand	SSP1	SSP4	SSP3	SSP2	SSP5	*Figure 3 of Riahi et al. 2017*
Cropland	SSP1	SSP4	SSP5	SSP2	SSP3	*Figure 4 of Riahi et al. 2017*
Forest	SSP3	SSP5	SSP4	SSP2	SSP1	
Pasture	SSP1	SSP5	SSP2	SSP3	SSP4	
Other Nature Land	SSP2	SSP3	SSP4	SSP5	SSP1	
CO2 Emissions	SSP1	SSP4	SSP2	SSP3	SSP5	*Figure 5 of Riahi et al. 2017*
Radiative Forcing	SSP1	SSP4	SSP2	SSP3	SSP5	
Projected Growth at End of Century (2100)	Lowest Growth				Highest Growth	

Figure 4: *Each SSP has a quantified future pathway describing its demographic, economic, energy, land use, and greenhouse gas emissions growth out to 2100. These rankings represent how the SSPs compare to one another in 2100 shown in order from lowest to highest growth for each category. To see details of the quantified pathways, please refer to Riahi et al. (2017).*

A GREAT LAKES REGIONAL PERSPECTIVE

GLISA is dedicated to bringing the most credible and usable climate information and data to practitioners in the Great Lakes region. Next, we share insights into important climate model considerations for our region, explain some of the data and RCP limitations we currently face, and propose a simple method for estimating RCPs when they are not readily available.

CLIMATE MODEL CONSIDERATIONS

Our team of climate experts within our Great Lakes Ensemble Project apply a requirement that climate models must explicitly simulate the Great Lakes and lake-land-atmosphere interactions for their projections to provide credible information for planning. It is important to note that many GCMs do not simulate lake dynamics. For this reason, GLISA has turned to using a set of dynamically downscaled climate projections produced specifically for the region, the University of Wisconsin's pairing of the International Centre for Theoretical Physics (ICTP) Regional Climate Model version 4 coupled to a one-dimensional lake model (UW-RegCM4). The UW-RegCM4 projections are only offered for RCP8.5 due to the high computational cost of dynamical downscaling. GLISA is working to develop a new set of state-of-the-art climate projections for practitioners in the Great Lakes region, based on improved lake simulations, and aims to provide additional RCPs in the future.

In the meantime, GLISA is investigating other existing dynamically downscaled projections to determine which may be suitable for use in our region. Our efforts have focused primarily on publicly available datasets including the North America Coordinated Regional Downscaling Experiment (NA-CORDEX) and the High Resolution Model Intercomparison Project (HighResMIP) from CMIP6. These and potentially other regional products are research areas that GLISA will be investigating over the coming years.

THE PROBLEM OF LIMITED RCPS (AND WHAT TO DO ABOUT IT)

Of the three publicly available project data sets discussed above, the UW-RegCM4 dataset is only available for RCP8.5, the NA-CORDEX dataset is only available for RCP4.5 and RCP8.5, and the CMIP6 HighResMIP data are being made available for SSP5-8.5 for HighResMip (Haarsma et al. 2016), likely involving RCP8.5. The limited number of available RCPs is due to the high computational cost of modeling. In the case that practitioners want to use an RCP that is not currently available, there are a few options to consider, listed below, each with its own set of strengths and weaknesses.

Option 1) **Use the RCPs that are available** from the most credible projections for your application, assess where gaps may exist in the information, and communicate those gaps to whomever is using the projections in decision making. This approach retains the original level of credibility in the model information, and works best when the available RCP is higher than the desired RCP. Lesser degrees of climate change can be potentially estimated from a high-end scenario but the reverse is not typically an option (changes are not necessarily linear). For quantitative estimates, please see guidance in option 3.

Option 2) **Lower your credibility standard** in model selection and consider using the larger set of CMIP5 and CMIP6 GCMs where every RCP is available in some fashion - some GCMs may provide all four RCPs and others may only provide a subset. The weaknesses of the models should be communicated to whomever is using the projections. This approach may be necessary if quantitative projections at several pathways are required, or if scenario uncertainty must be quantified. If the benefits of expanding the model selection come at the cost of having to use models that no longer provide meaningful information, GLISA recommends option 1 or option 3 instead.

Option 3) **Estimate unavailable RCPs** for downscaled projections using differences in the underlying GCMs as a guide. This approach relies on differences between RCPs for the underlying GCMs (of which more RCPs are typically available). The magnitude of those differences can be used as a conversion factor to estimate unavailable RCPs in the downscaled projections when expert judgement supports it. For example, the difference between, say, mean temperature projections under RCP8.5 and RCP6.0 can be used as a "conversion factor" for downscaled RCP8.5 data to estimate downscaled RCP6.0 when it is not otherwise available. This process is depicted in Figure 5. GLISA

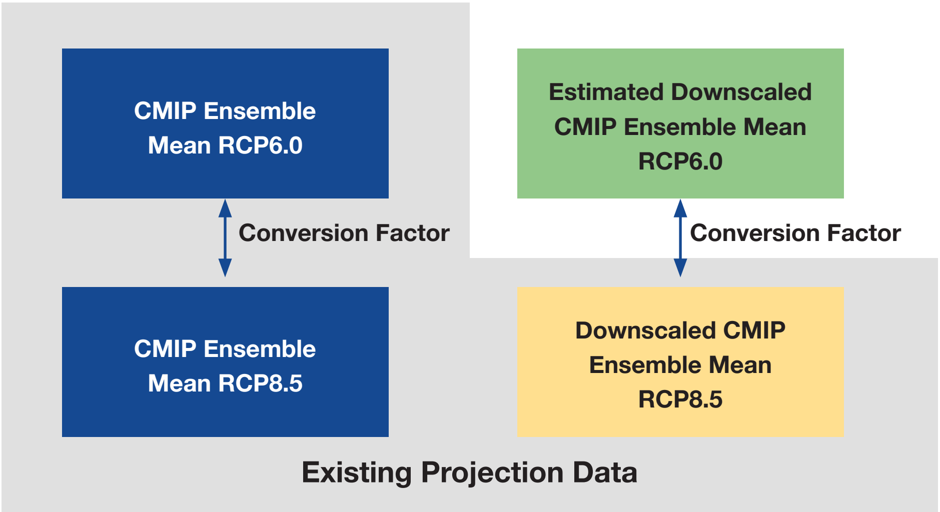


Figure 5: *Concept diagram depicting our process for estimating RCPs. Hypothetical existing climate projection data from the CMIP ensemble under multiple RCPs (blue) and a downscaled CMIP product for a single RCP (yellow) are shown on top of the gray background. Both data sets have RCP8.5 in common, so the difference between CMIP projections of RCP6.0 and RCP8.5 is used as a conversion factor to estimate RCP6.0 (green box) for the downscaled product.*

recommends first assessing model uncertainty for each variable and to only proceed when the models agree on the sign (e.g., increasing or decreasing) of future climate changes. At best, GLISA recommends using this approach on seasonal or annual averages and not as a means to recreate daily time series or finer-scale information. This approach requires transparency when providing estimated projections for decision making, or any other use, because projection estimates are more uncertain than the original projection data. We conduct Option 3 next for temperature and precipitation projections and share our guidance on conversion factors.

ESTIMATING UNAVAILABLE RCPS: A GREAT LAKES CASE STUDY

For a given climate model, different RCPs can result in different possible climate futures (e.g., changes in temperature, precipitation). If practitioners want to use more than one RCP in their planning, knowledge about these climate differences is important to consider. In the case that the determined best available climate projections are only offered for select RCPs, estimates of other RCPs can be calculated in some instances. These estimates will likely look different depending on the climate variable of interest, like temperature and precipitation, and GLISA advises all estimation procedures be clearly communicated to end users. RCP estimates should primarily be used to spur conversation and discussion around the use of various emissions pathways. **The estimates introduce another layer of uncertainty, so they should not be framed as a climate projection but as supplemental information.** Next, we present a case study for how to develop estimates of RCPs.

GLISA frequently uses the UW-RegCM4 projections in adaptation work, based on our extensive evaluation of the data and determination that they offer more credible information for planning in our region compared to other projection data sets. One drawback of these projections is they are based on a single RCP, RCP8.5, due to the high computational cost of the regional modeling, in this case dynamical downscaling. Practitioners often desire lower RCPs for comparison in their work. Using Option 3 above, we provide an example of how to estimate other RCPs for the UW-RegCM4 projections.

We first characterize known differences between RCPs (RCP2.6, RCP4.5 and RCP8.5) using the full CMIP5 ensemble. Regional averages of temperature and precipitation projections are computed, and the differences (i.e., deltas) under different RCPs become the conversion factors in our estimation. We then apply those differences to the UW-RegCM4 dataset, which consists of six CMIP5 GCMs that were dynamically downscaled for RCP8.5. Using this approach, we are able to estimate RCP2.6 and RCP4.5 for the UW-RegCM4 projections. We rely on existing products, the Climate Science Special Report (USGCRP 2017) and an Intergovernmental Panel on Climate Change (IPCC) 2014 Synthesis Report, to develop our conversion factors. These products were chosen because they include maps of CMIP5 projections for multiple RCPs (RCP2.6, RCP.5 and RCP8.5) (Figures 6, 7, and 8). Maps of RCP6.0 were not available in these products for us to integrate into our synthesis.

We suggest a more robust method, when time and resources allow, is to calculate conversion factors on a model by model and grid-cell by grid-cell basis. This method would better capture information about specific models that are used in the estimation and the spatial variability of projection information due to RCP. For example, if you want to know the RCP2.6 projection for RegCM4-CNRM, then you would compute deltas across the domain of CNRM at RCP2.6 and RCP8.5 and apply those deltas to the domain of the downscaled RegCM4-CNRM RCP8.5 projection.

TEMPERATURE PROJECTIONS

- Temperature projections from different RCPs do not differ much from one another until after mid-century (2050). Practitioners seeking projections for mid-century or earlier can use any available RCP.
- After mid-century, there is about a 2°F increase between projections from RCP2.6 and RCP4.5 and another 4°F increase between RCP4.5 and RCP8.5 over the Great Lakes region.

In general, temperature projections under different RCPs share relatively similar spatial patterns (e.g., temperature increases are greater over land compared to oceans and

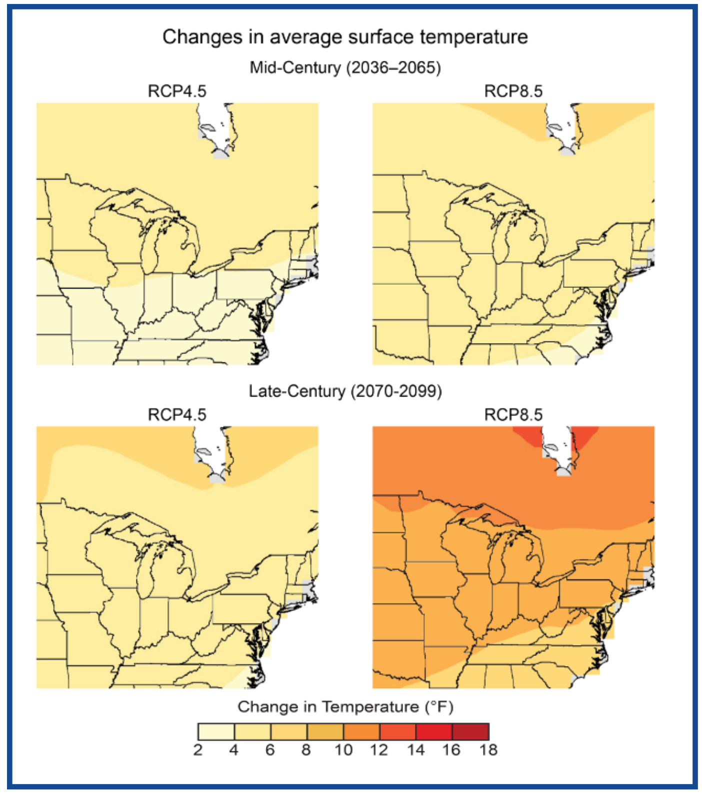


Figure 6: Projected changes in annual average temperatures (°F) across the Great Lakes region. Changes are the difference between the average for mid-century (2036–2065; top) or late-century (2070-2099, bottom) and the average for near-present (1976–2005). Each map depicts the weighted CMIP5 multimodel mean. Increases are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change). Figure adapted from the Climate Science Special Report Figure 6.7 (USGCRP, 2017).

greatest in northern latitudes), but higher emissions pathways represent more rapid change. Across the Great Lakes region, there is very little difference between RCPs at any time horizon except for RCP8.5 at late-century (Figure 6). RCP8.5 at late-century emphasizes a rapid rate of temperature increase.

The maps in Figure 6 represent the CMIP5 ensemble mean, or the average of over 30 models. The average can be misleading if individual models tell very different stories about the future, but there is strong agreement among all CMIP5 GCMs that future temperatures will increase. The dots in Figure 7 show where over 90% of the models agree that temperatures will increase and there is a strong climate change signal (i.e., the amount of projected change is large compared to natural variability).

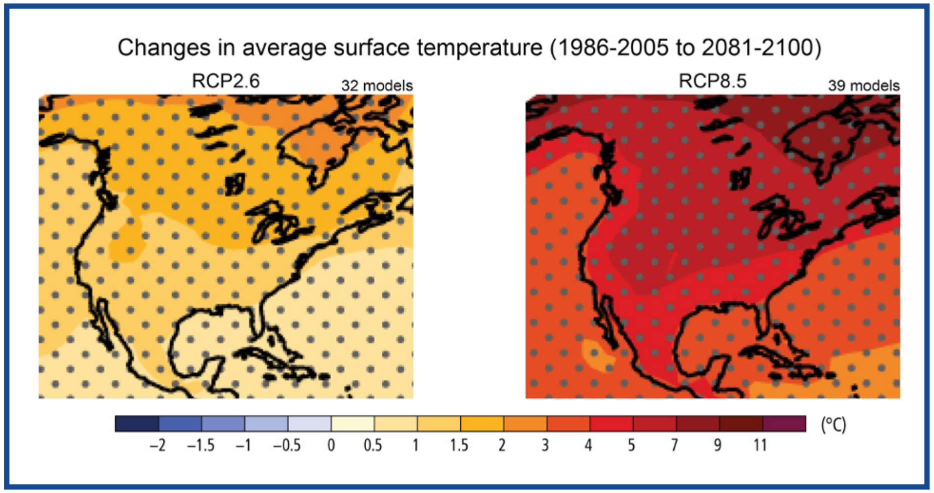


Figure 7: *Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model mean projections (i.e., the average of the model projections available) for the 2081–2100 period under the RCP2.6 (left) and RCP8.5 (right) scenarios for change in annual mean surface temperature (°C). Changes are shown relative to the 1986–2005 period. The number of CMIP5 models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (dots) indicates regions where the projected change is large compared to natural internal variability (i.e., greater than two standard deviations of internal variability in 20-year means) and where 90% of the models agree on the sign of change. Adapted from the IPCC Synthesis Report (2014) Figure 2.2*

Since CMIP5 temperature projections under different RCPs share similar spatial patterns and have strong agreement for the sign of change, we propose they offer a foundation to estimate temperature differences in other datasets where one or more RCP is unavailable. We start by tabulating differences between RCPs for our region. Table 2 shows quantified temperature projections for the Great Lakes region using different RCPs at mid- and late-century based on the maps in Figure 6.

Table 2: *CMIP5 projections of annual temperature change for the Great Lakes region under multiple RCPs at mid-century (2036–2065) and late-century (2070-2099).*

	Mid-Century	Late-Century	Notes	Source
RCP2.6	***+2 to 4°F***	***+2 to 4°F***	*The source figure reports +1 to 2°C which is equivalent to +2 to 4°F*	*IPCC AR5 Figure 26-3*
RCP4.5	***+2 to 6°F***	***+4 to 6°F***	*At mid-century, the southern part of the region (IL, OH, IN, PA, and NY) is in the +2 to 4°F zone and the northern states and Ontario are in the +4 to 6°F zone, so the entire range is reported (+2 to 6°F).*	*Figure 6*
RCP8.5	***+4 to 6°F***	***+8 to 10°F***	*At late-century, northern MN and parts of Ontario reach the +10 to 12°F zone, but this was omitted from the table since it only covers a small part of the region.*	*Figure 6*

Next, we expand Table 2 to quantify differences, or create "conversion factors", between projections for different RCPs and time periods, which we use as a basis for estimating missing RCPs in the UW-RegCM4 projections. Table 3 shows our calculation of conversion factors for CMIP5 RCPs. Table 3 can be read across rows, which shows temperature differences between a late-century projection and its mid-century projection, or vertically, which shows how different one RCP is from another. When the conversion factor increases nonuniformly, such as increasing the temperature at only one end of the projected range, this is the product of a new, warmer, temperature zone entering part of the region while maintaining part of the temperature zone that was already there. An example of this is going from RCP4.5 to RCP8.5 at mid-century (see maps in Figure 6), where two temperature zones characterize RCP4.5 but only one temperature zone is over the region in RCP8.5. When the entire range shifts, this is a product of a completely new temperature zone entering the region (e.g., going from mid- to late-century in RCP8.5).

A few interesting observations emerge from Table 3. Temperatures in RCP2.6 are roughly the same at mid- and late-century. This is because global emissions are mitigated to a point where they are negative (i.e., more are taken out of the atmosphere than put into the atmosphere). An incremental increase of 2°F is required to go from RCP2.6 to RCP4.5 at both mid- and late-century. Another increase of 2°F is required to jump to RCP8.5 at mid-century, but 4°F is required at late-century. Going from mid- to late-century, there is no additional temperature increase in RCP2.6; the temperature range increases by 2°F (at the low end) in RCP4.5 and 4°F in RCP8.5. As expected, RCP8.5 has the most rapid temperature increase after mid-century.

Table 3: *CMIP5 ensemble mean projections of annual temperature change over the Great Lakes region are shown (light gray text) for three RCPs (RCP2.6, RCP4.5, and RCP8.5) at mid- and late-century. The reported range represents the range of temperatures over the Great Lakes region (see Table 2). Conversion factors are calculated by taking the difference between RCPs (columns) and between the mid- and late-century projection for the same RCP (rows). For example, the mid-century projection at RCP2.6 is +2 to 4°F and at RCP4.5 is +2 to 6°F. At the lower end of these ranges, there is no change (+2 to +2) but at the higher end there is an increase of 2°F (+4 to +6°F). So, to convert from RCP2.6 to RCP4.5 at mid-century, add 2°F to the upper bound of the projection. These conversion factors are relevant for any projections based on the CMIP5 GCMs.*

	Mid-Century	Convert Mid- to Late-Century	Late-Century
RCP2.6	**+2 to 4°F**	There is no change between the RCP2.6 mid- and late-century projection	**+2 to 4°F**
	To convert RCP2.6 to RCP4.5 at mid-century add +2°F to the projection's upper bound		To convert RCP2.6 to RCP4.5 at late-century add +2°F to the projection's lower and upper bounds
RCP4.5	**+2 to 6°F**	To convert RCP4.5 from mid- to -late century add +2°F to the projection's lower bound	**+4 to 6°F**
	To convert RCP4.5 to RCP8.5 add +2°F to the projection's lower bound		To convert RCP4.5 to RCP8.5 at late-century add +4°F to the projection's lower and upper bounds
RCP8.5	**+4 to 6°F**	To convert RCP8.5 from mid- to -late century add +4°F to the projection's lower and upper bounds	**+8 to 10°F**

Using the conversion factors in Table 3, we start with UW-RegCM4 temperature projections from RCP8.5 at mid- and late-century and estimate RCP2.6 and RCP4.5 for both time periods (Table 4). Since we are starting with RCP8.5, we have reversed the order of the conversion factors to work our way up the table (instead of down). All of our estimates are based on converting from a higher to lower RCP for a given time period (using columns from Table 3 instead of rows). Our estimated temperature projections for RCP2.6 and RCP4.5 offer new information for planning that can help to frame future uncertainty. The only estimate that stands out is the RCP2.6 estimate for late-century, which at its low end is lower than its mid-century projection. Even so, the difference is only 1°F and the average of the RCP2.6 late-century projection equals the mid-century projection, like we find in our conversion table (Table 3).

Table 4: *UW-RegCM4 ensemble mean projections of annual temperature change over the Great Lakes region are shown for RCP8.5 and two estimated RCPs (RCP2.6 and RCP4.5) at mid- and late-century.*

	Mid-Century	Late-Century
Estimated RCP2.6	**+2°F**	**+1 to 3°F**
	To convert RCP4.5 to RCP2.6 at mid-century subtract 2°F from the projection's upper bound	To convert RCP4.5 to RCP2.6 at late-century subtract 2°F from the projection's lower and upper bounds
Estimated RCP4.5	**+2 to 4°F**	**+3 to 5°F**
	To convert RCP8.5 to RCP4.5 subtract 2°F from the projection's lower bound	To convert RCP8.5 to RCP4.5 at late-century subtract 4°F to the projection's lower and upper bounds
Simulated RCP8.5	**+4°F**	**+7 to 9°F**

We offer Table 3 as an annual temperature conversion chart for any projection data for the Great Lakes region based on the CMIP5 GCMs. The CMIP5 projections we based this analysis on are an average of over 30 models, so we suggest conversions of annual temperature projections using these conversion factors should be applied to multi-model averages as opposed to converting individual models. As noted earlier, model by model conversions may offer more robust information.

This conversion chart, or any similar chart that is produced, can be tested in theory by approximating a projection that already exists. This exercise can be conducted to gauge the credibility of the estimation method. In our example, downscaled projections for RCP8.5 were available for mid- (+4°F) and late-century (+7 to 9°F). The conversion factor for mid- to late-century for RCP8.5 is +4°F (Table 3). Adding 4°F to the mid-century RCP8.5 projection of 4°F yields 8°F, which is within the range of the simulated late-century projection (+7 to 9°F). This shows that our conversion factor produces a reasonable estimate.

PRECIPITATION PROJECTIONS

- Precipitation projections vary more based on the choice of climate model than the underlying RCP.
- Precipitation projections should not be used to estimate unavailable RCPs, because there is disagreement among the CMIP models in their future precipitation trends.
- Practitioners should work with climate service providers to select precipitation projections from individual models that offer divergent future scenarios to explore.

Climate models do not consistently agree on future precipitation changes in the Great Lakes region because precipitation processes are difficult to simulate. In addition, there are local and regional factors that modify precipitation patterns, like the presence of lakes,

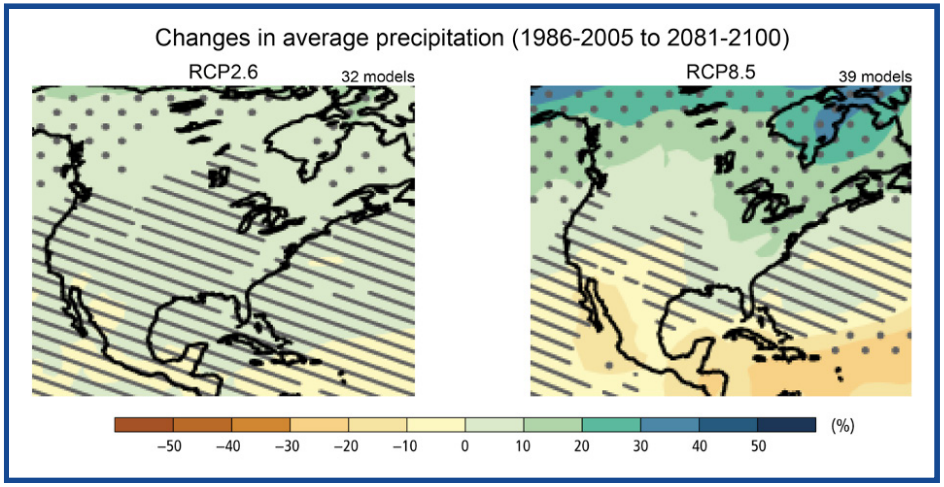


Figure 8: *Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model mean projections (i.e., the average of the model projections available) for the 2081–2100 period under the RCP2.6 (left) and RCP8.5 (right) scenarios for change in average precipitation. Changes are shown relative to the 1986–2005 period. The number of CMIP5 models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (dots) indicates regions where the projected change is large compared to natural internal variability (i.e., greater than two standard deviations of internal variability in 20-year means) and where 90% of the models agree on the sign of change. Hatching (diagonal lines) shows regions where the projected change is less than one standard deviation of natural internal variability in 20-year means. Adapted from the IPCC Synthesis Report (2014) Figure 2.2*

which GCMs may or may not capture well. Figure 8 highlights the disagreement in future precipitation projections among models, especially in RCP2.6, for the Great Lakes region. The lack of dots over the Great Lakes region in Figure 8 indicates greater disagreement among models, and the diagonal lines over the Great Lakes region indicate the projected changes are relatively small for RCP2.6. Most likely, projections from individual models may be much larger, but the ensemble mean that is represented in the figure converges towards zero when some models project positive changes and some negative. In RCP8.5, the climate change signal is stronger (i.e., projected changes are larger) and dots in the northern part of the region indicate greater agreement among models that precipitation will increase. **Lack of model agreement does not support a case for using the GCMs as a basis for developing conversion estimates of precipitation like for temperature.**

However, there is a lot of overlap between RCPs when we look at annual precipitation projections over time, eliminating the need for conversion factors. Different RCPs do not offer substantially different information for planning. For example, Figure 9 shows a set of statistically downscaled CMIP5 precipitation projections by season for the Great Lakes region. During the Summer and Fall, there is almost no difference between RCP4.5 (blue line) and RCP8.5 (red line). Both the mean and the variance of 30 models shows roughly the same amount of precipitation for the entire time series. Winter and spring projections show RCP8.5 projecting slightly more precipitation than RCP4.5 near the end of the century, but when you look at the range of all models, indicated by the red and blue shading, there is strong overlap between the different RCPs. In addition, even

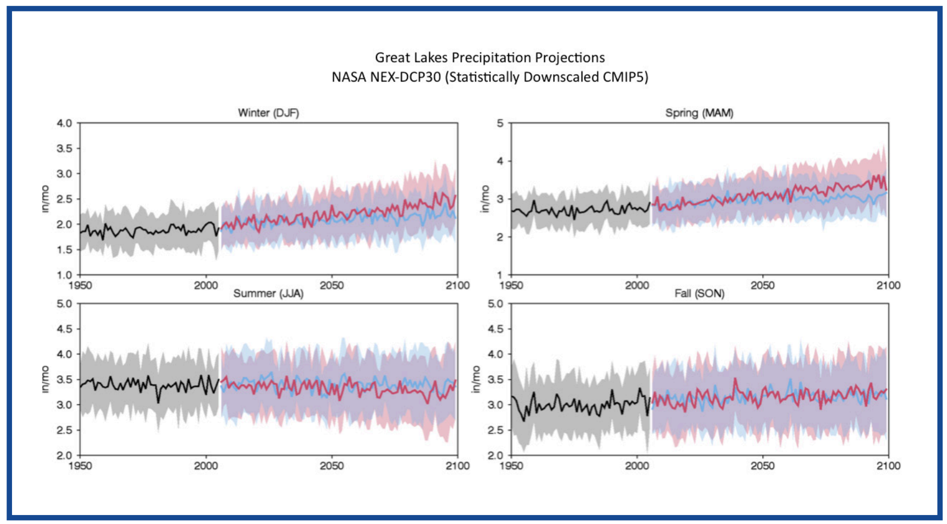


Figure 9: *Great Lakes seasonal average time series of precipitation for historical (black), RCP4.5 (blue), and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The average of 30 CMIP5 models is indicated by the solid lines, and their standard deviations are indicated by the respective shaded envelopes. Figure source: U.S. Geological Survey - National Climate Change Viewer Summary of the Great Lakes Region Figure 3*

at the end of the century, both RCPs have some models that produce seasonal precipitation totals that fall within the range of historical observations (part of the red or blue shading overlaps values within the gray shading).

The choice of model(s) plays a larger role in future precipitation projections than the time frame or the RCP considered. We recommend practitioners work with climate service providers to identify precipitation projections that offer diverse futures to explore, independent of the available RCPs. Those futures can be framed into scenarios and tailored to the practitioner's problem to offer relevant information for planning.

CONCLUDING REMARKS

This Guide is intended to help practitioners better understand the scenarios used in climate modeling so that they can make informed decisions about which climate projections they want to use in their work. Our Quick-Step Guide summarizes the order of choices practitioners have when it comes to selecting climate projections. The Climate Model Selection step is not trivial, so there is great benefit in partnering with a climate service provider to ensure the most credible and reliable projections are being considered. After reading this Guide we anticipate the next steps to be more intuitive based on our overview of the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs); practitioners can know the underlying socioeconomic and climate forcing assumptions of different climate projection data sets and make their selection(s) based on the type of future they want to explore.

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Adaptation: The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects. (Taken from IPCC AR5 WG2 Glossary)

Baseline Scenarios: RCPs that do not include any specific climate mitigation target.

Business as Usual: A term used to describe a scenario pathway where socio-economic development follows current trends.

Climate Forcing: Factors that drive changes in Earth's climate, such as greenhouse gas emissions and land use change.

Climate Model: A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes, and accounting for some of its known properties. (Taken from IPCC AR5 WG2 Glossary)

Climate Projections: The simulated response of the climate system to a scenario of future climate forcing (e.g., emission or concentration of greenhouse gases and aerosols) generally derived using climate models. (Adapted from the IPCC AR5 WG3 Glossary)

Climate Service Provider: An individual or organization providing customized climate data or information to clients.

Credible: Perceived as meeting standards of scientific plausibility and technical adequacy (Cash et. al, 2002).

Dynamically Downscaled: Finer spatial scale in climate projections is achieved using high-resolution regional climate models that aim to better capture regional climate processes compared to their coarser GCM counterparts.

Energy use: Consumption of energy from the sectors: solar/wind/geothermal, hydro, bio-energy, nuclear, natural gas, oil and coal.

Ensemble: A group of climate model simulations as opposed to a single climate model projection.

Fine-Resolution: More grid cells of a smaller size are used when running a climate model. This enables the results of the run to have more spatial detail than a model run with fewer, larger grid cells. The value of this additional spatial detail depends on whether important climate processes are resolved, or simulated, at that finer scale.

Global Climate Model/General Circulation Model (GCM): Numerical models representing physical processes in the atmosphere, ocean, cryosphere and land surface. (Source: Climate.gov Climate Data Primer)

Greenhouse Gas (GHG): Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary GHGs in the earth's atmosphere. (Adapted from the IPCC AR5 WG3 Glossary)

Integrated Assessment Models (IAMs): Integrated models explore the interactions between multiple sectors of the economy or components of particular systems, such as the energy system. Integrated models may also include representations of the full economy, land use and land cover change, and the climate system. (Adapted from the IPCC AR5 WG3 Glossary).

Intergovernmental Panel on Climate Change (IPCC) assessments: Recurring global scientific climate assessments.

Land Use/Land Cover Change: Changes in the use of land, like growing food, cutting trees, or building cities, and/or changes in the physical characteristics, or "cover", of the land surface such as concrete, trees, and crops.

Mitigate/Mitigation: A human intervention to reduce the sources or enhance the sinks of greenhouse gases. (Taken from IPCC AR5 WG2 Glossary)

Mitigation Scenario: An RCP that includes assumptions about global mitigation efforts.

Model Output: Data variables that are outputs from climate models (e.g., temperature, precipitation, solar radiation, etc.)

Model Uncertainty: Differences between climate projections due to the choice of climate model.

Natural Variability: Climate variability due to natural (nonhuman) causes, such as volcanic eruptions, subtle changes in the Earth's orbit, and events caused by the interactions between the atmosphere and ocean such as El Niño.

Practitioners: Anyone who is using or wanting to use climate data or information. A practitioner may be a city planner, a watershed manager, a Tribal resource manager, or any number of people who are interested in or already using climate data and/or climate information in their work.

Representative Concentration Pathways (RCPs): RCPs are radiative forcing scenarios, based primarily on the amount of radiative forcing present at the end of the 21st century. RCPs were used to "drive" the CMIP5 GCMs as part of the IPCC Fifth Assessment Report.

Radiative Balance: The relationship between the amount of energy an object receives and the amount of energy an object emits or gives off. In the climate context, the "object" is Earth.

Scenario: Quantitative pathways and qualitative storylines of the future.

Scenario Uncertainty: Differences between future climate projections due to the RCP that is used to drive the climate model.

Shared Socioeconomic Pathways (SSPs): Different scenarios that describe how society might evolve in the future. This includes speculation about different variables such as population growth, income inequality, and energy use/demand.

Socioeconomic: Including factors such as population, gross domestic product, and other socioeconomic factors relevant to understanding the implications of climate change.

Temperature Zone: In this document, a region of similar temperature change.

Unsustainable: A state where the equitable persistence of natural and human systems can not be achieved. (Adapted from IPCC AR5 WG2 Glossary)

Usable: In a condition or format that can be readily applied.