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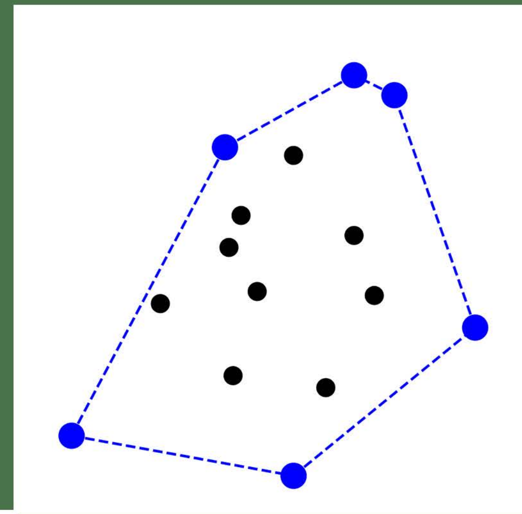
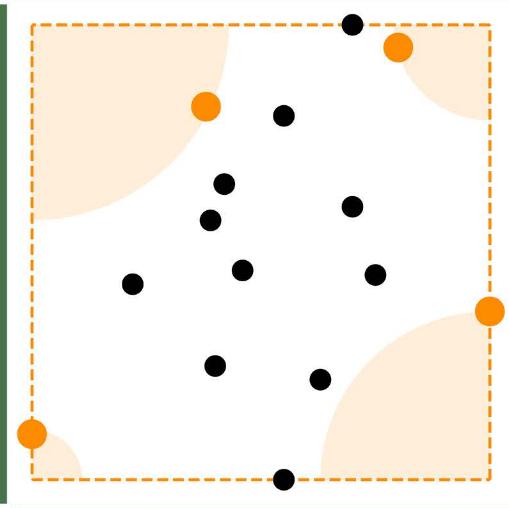
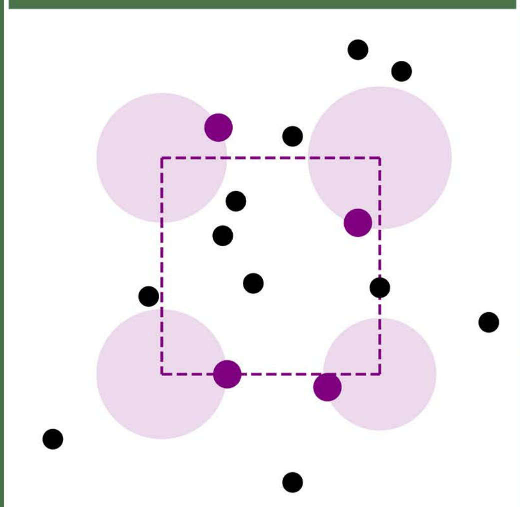
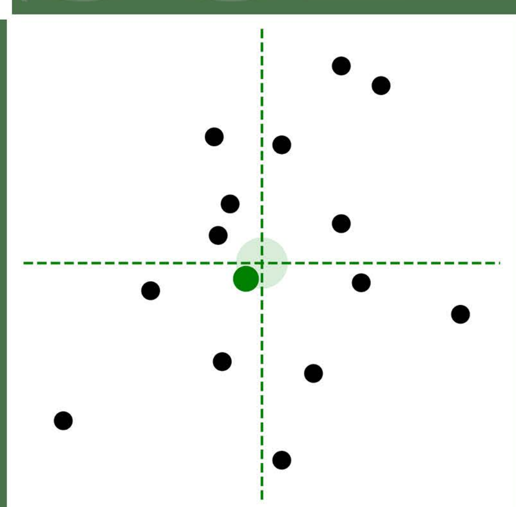






A Systematic Approach for Selecting Climate Projections to Inform Regional Impact Assessments



Office of Research and Development
Center for Public Health & Environmental Assessment
Health & Environmental Effects Assessment Division

EPA/600/R-20/309
August 2020
FINAL

A Systematic Approach for Selecting Climate Projections to Inform Regional Impact Assessments

Center for Public Health and Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC

DISCLAIMER

ABSTRACT

The increasing volume of climate model output creates challenges for those seeking to understand or use those projections in a way that is scientifically sound, but also efficient with respect to time and resources. A common approach to resolving these competing goals is to identify a subset of the available climate projections that still describes the relevant characteristics of the entire suite. This report synthesizes and describes alternate approaches for systematically identifying a set of climate projections that are best suited for a user-defined research question or objective. The advantages and disadvantages of these approaches are highlighted, and generally depend on a tradeoff between including more (lower risk tolerance) or fewer (less information to process) climate projections. This report provides information in the context of a new Web-based tool: Locating And Selecting Scenarios Online (LASSO). The LASSO tool automates much of the selection process by guiding users through a step-by-step procedure of first building a scatterplot visual representation of a suite of climate projections, then assisting the user in identifying the projections that most closely align with their specific concerns or questions. The report presents four approaches for sub-setting climate projections that are generally suitable for a variety of applications and includes exemplars for each of the EPA Regions. The tool includes a much larger suite of pre-computed scatterplots, maps, and spatial data that describe climate projections by EPA Region, state (contiguous), two scenarios, and both annual and seasonal summaries.

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LIST OF ABBREVIATIONS AND ACRONYMS

CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
EPA	Environmental Protection Agency
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
LASSO	Locating And Selecting Scenarios Online
RCM	Regional Climate Model

AUTHORS AND REVIEWERS

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AUTHORS

U.S. EPA

Philip Morefield

ICF International, Washington, D.C.

Judsen Bruzgul, Brad Hurley, and Hannah Wagner

REVIEWERS

U.S. EPA Reviewers

Christopher Weaver (ORD/CPHEA), Alexandra Dichter (Region 1/OARM)

External Peer Reviewers

Timothy Kittel (Univ. of Colorado), Amy Snover (Univ. of Washington), Claudia Tebaldi (NCAR)

QUALITY ASSURANCE

This report has been reviewed and adheres to EPA QA and peer review policy requirements. The work for LASSO was conducted under an approved EPA ORD Quality Assurance (QA) Project Plan, *Improving data availability and functionality of the LASSO Tool*, and has undergone internal technical review and external peer review. It is of known and acceptable quality to support its intended use.

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1. EXECUTIVE SUMMARY

Advances in both the scientific understanding of the climate system and the capability to produce climate simulations have led to a growing number of new and updated projections of future climate suitable for use in impacts, vulnerability, and risk assessments in the United States. The volume and complexity of this information present immense challenges for non-specialists attempting to identify relevant projections for their specific analytic or assessment needs. This report presents a practical approach for selecting climate projections, which are simulated responses of the climate system based on a set of assumptions about changes in natural and anthropogenic forcings. Specifically, it provides guidance to help users answer the question, *which climate projection(s) should I use?* It accomplishes this by helping users visualize strategies for capturing the key uncertainties represented by all the available model projections, using a manageable number of representative projections that can serve as input into their analysis or assessment.

The report's primary audience is U.S. Environmental Protection Agency (EPA) Regional staff who may have limited familiarity with outputs from General Circulation Models (GCMs) or underlying scenarios, but still seek a robust approach for integrating future climate information into analyses or assessments that will support decision making at a regional level. Additionally, the information in this report may be useful to anyone who needs U.S. climate projections for analyzing impacts from long-term changes in temperature or precipitation patterns.

The report presents a practical approach for selecting climate projections with the aid of an EPA online tool called LASSO (Locating And Selecting Scenarios Online). It also provides a set of figures describing climate projections for each EPA Region, generated from LASSO results.

Readers of this report will come away with the following:

1. An understanding of some key considerations for identifying climate information that can be used to address decision needs.
2. A practical approach for selecting climate projections for meeting these needs, including the function of the LASSO tool and strategies for using it to identify a manageable but representative subset of projections.
3. Additional basic reference information about climate projections and available climate models (GCMs), considerations related to selecting relevant model projections, and the benefits of the LASSO approach.

Need and Rationale for Scenario Selection

In seeking climate projections for an analysis or assessment, analysts confront the contradictory goals of: (i) addressing deep uncertainties by describing a broad range of potential future climates and (ii) minimizing the number of climate models included in the analysis in the interest of practical time and resource constraints. Maximizing the range of futures helps bound uncertainties that span future scenarios as well as the range of unique climate model projections under those scenarios. Minimizing the number of climate models is necessary to ensure the assessment remains manageable within time and resource constraints, and that a coherent conclusion can be reached and communicated. The LASSO tool design helps the user systematically, transparently, and efficiently balance these tradeoffs.

Identifying Climate Information Needs

The climate information used to support impact and vulnerability analysis should reflect the decision-making context. While each analysis will have unique objectives and constraints, analysts can consider several key elements when identifying climate information needs:

- Temporal resolution and time horizon
- Spatial resolution of the affected area
- Risk or uncertainty tolerance of the decision maker
- Relevant climate variables

This report provides an overview of each of these elements and describes how they influence climate information needs.

EPA's LASSO Tool: A Practical Approach to Selecting Climate Projections

EPA's LASSO tool aims to streamline the process of selecting appropriate data for an analysis, while at the same time reducing the overall volume of data that the analyst will need to work with. The tool generates scatterplots of model projections for a specific EPA Region, timeframe, and scenario, with selected climate parameters (such as precipitation and temperature) on each axis. The user can then employ one of the projection selection strategies described in this report to quickly and easily identify a manageable subset of projections that bound the range of a larger group of projections in two dimensions simultaneously. The report describes four strategies for identifying subsets of projections (*Lasso*, *Four Corners*, *Middle Corners*, and *Double Median*) and discusses their advantages and disadvantages. Future versions of LASSO may include additional features and functionality.

Background on Scenarios, Models, and Selection Criteria

Climate models cannot simulate future changes without relying on assumptions about the future variability of environmental factors that affect the global climate system. Because the future can never be predicted with absolute certainty, climate scientists have developed a range of scenarios that depict different possible pathways, which in turn lead to different combinations of future climate forcings. Climate models use these scenarios to project (rather than predict) how the climate would change under each hypothetical scenario. Climate research centers around the world have developed many models of global and regional climate, each of which generates somewhat different projections of future climate under the same scenario.

Under such currently irreducible uncertainty, an optimal approach to selecting climate projections would incorporate as many climate projections as possible, perhaps including all models and scenarios available. However, given the large number of potential combinations of climate scenarios and models, attempting to select all data can be time-consuming, resource-intensive, and a strain on data processing capabilities. Spending time at the outset to clearly identify what climate information is needed to support the analysis can help an analyst identify selection criteria to reduce the number of projections while still providing enough information to be useful for decision making. The report describes potential selection criteria to consider, including consistency with global projections, physical plausibility, applicability in impact assessments, representativeness, accessibility, vintage, resolution, and validity. This report also provides an overview of the need to consider interrelationships among models, some of which share some of the same code base, in order to properly interpret projections from a range of models.

Conclusion

The practical approach presented here and operationalized in the LASSO tool can assist analysts and others with the task of selecting specific climate projections from a range of climate models and scenarios to inform analyses of potential impacts and vulnerabilities. By considering the climate information needed to support decision making, users can employ the approach best suited to the decision context and analytical constraints. The example scatterplots provided within this report provide a readily accessible starting point for those working in EPA Regions across the country.

2. INTRODUCTION AND BACKGROUND

- **Users must balance selecting more projections to better capture uncertainty and/or reduce risk with selecting fewer projections due to practical constraints**
- **Requirements and objectives of a specific decision should guide selection of relevant climate information**
- **To ensure climate information will be useful to the needs of decision makers, consider temporal resolution and the decision time horizon, spatial resolution, tolerance for risk, and relevant climate variables.**

2.1 PURPOSE AND SCOPE OF REPORT

2.1.1 Context

As the study of future climate impacts and vulnerability continues to evolve, new and updated climate model outputs are being produced that incorporate the latest and best understanding of the global climate system. At the same time, new methods and approaches are continually being developed to regionalize or "downscale" these global climate model outputs to finer spatial resolutions more useful in studies of potential future impacts. While this new information can play a critical role in the assessment of future climate risks, both the increasing volume and complexity of information can make locating and identifying the most relevant and useful projections of future climate for a particular application a confusing, laborious, and technically challenging task (Moss et al., 2014). This is particularly true because, despite the many significant advances in our understanding of the climate system, important aspects of future climate remain impossible to predict, and climate projections are thus subject to intractable uncertainties that cannot be fully accounted for in future climate studies.

Key Terms

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. In order to develop projections, climate models rely on a set of assumptions about air pollution and land use change (scenarios or pathways) (IPCC, 2014).

Climate Projection or Simulation: The simulated response of the climate system to a scenario or pathway of future concentrations of air pollutants, natural climate forcings, and other factors derived using climate models (IPCC, 2014).

Consequently, analysts or decision makers who need regional projections of future climate to support a specific need or address a specific question are presented with an overwhelming number of data sources and unique model projections from which to choose. They can thus benefit from simple tools designed to efficiently scan and concisely summarize large volumes of climate model output, while working within a framework of straightforward, practical strategies for selecting the most relevant outputs for their purposes.

2.1.2 Scope

In recognition of these challenges, this document provides information on practical, systematic approaches for selecting a relevant and useful subset of climate projections from existing sources of climate model output, to readily inform analyses of change impacts and vulnerabilities.

The report is intended to be most useful for those with at least a modest understanding of climate scenarios and projections whose aim is to integrate future climate information into assessments to inform decision making at a regional level. The information in this report should also be relevant to analysts conducting climate-related studies at national or local scales, and decision makers seeking additional background on the range of potential future climate for a given area. The practical approach for selecting climate projections is discussed in the context of a new EPA online tool called LASSO (Locating And Selecting Scenarios Online), which assists in the implementation of projection selection strategies.

This report is a resource that helps answer the question, *which climate projections should I use?* It accomplishes this by helping users visualize strategies for capturing key uncertainties represented by dozens of available model projections, and then identifying a manageable subset of representative projections that serve as input into a given analysis or assessment. The report presents principles that can be used to select climate information for analysis based on factors such as time horizon, spatial resolution, risk tolerance, and climate variables of interest. It focuses on the process of selecting and obtaining raw data sets from online climate information sources, rather than obtaining climate impact analysis and synthesis products. While this report does not provide technical guidance on the use of raw climate data in vulnerability and impact assessments, it includes references to sources of information that may be useful to that end. Figure 1 shows the overall steps in the scenario selection process.

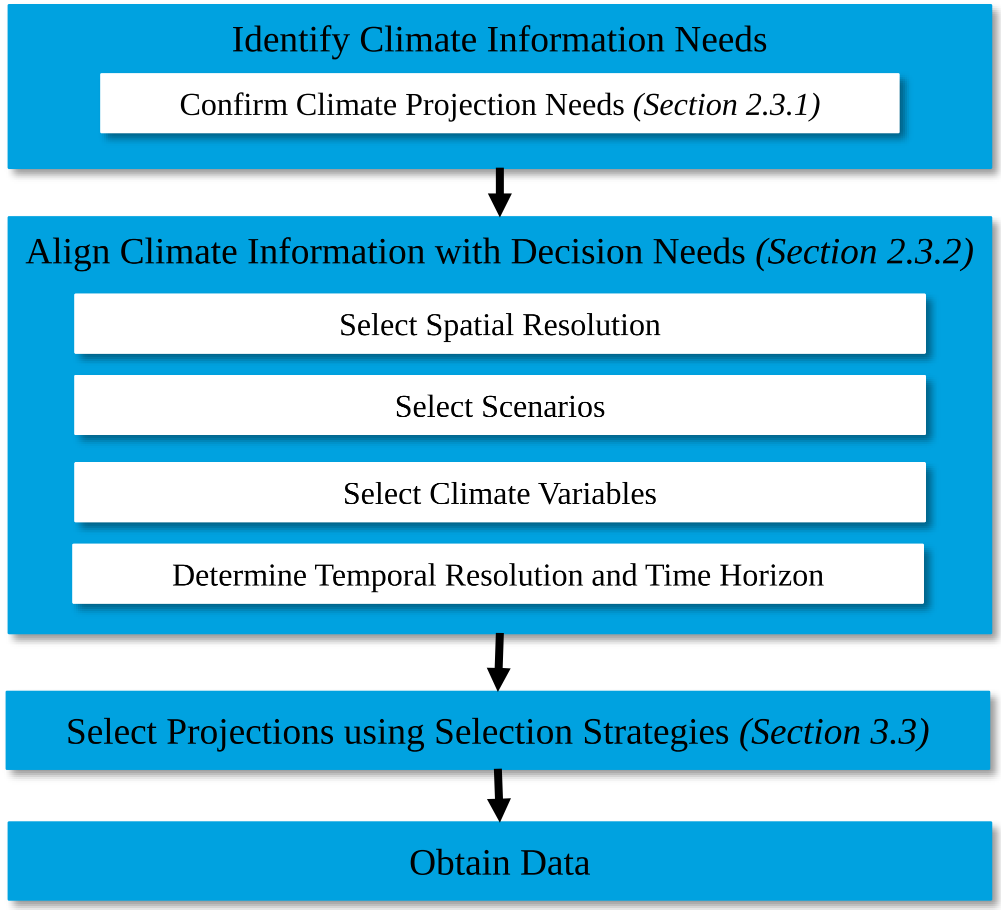

Figure 1. Overview of approach for selecting climate projections to inform regional impact assessments

This report is organized to allow the user to efficiently obtain the information needed to complete the process for selecting climate projections. Section 2 describes the context, scope, and need for the scenario selection process. This section also provides context for identifying climate information needs. Section 3 outlines the steps and decisions involved in using the LASSO tool. Sections 2 and 3 provide enough information for experienced analysts to understand the approach and use the LASSO tool to help them select climate projections. Section 4 provides detailed background and additional reference information that may be useful for readers seeking more technical information on climate projections or who want to dive deeper into particular topics. The report indicates areas where readers may refer to Section 4 to further their understanding and knowledge.

2.2 NEED AND RATIONALE FOR SCENARIO SELECTION

It has been demonstrated that identifying or ranking the "best" climate models based on an ability to replicate historical climate does not result in a more confident prediction about future climate (Kunti et al., 2010; Pierce et al, 2009; Santer et al., 2009; Brekke et al., 2008; Coquard, 2004). Instead, when using climate information for an analysis or assessment, an ideal approach is to use information from all available climate models. Using all possible projections allows one to consider the full range of plausible futures, which is consistent with approaches seeking robust decisions in the face of uncertainty about the future environment (Weaver et al., 2013). We lack the ability to confidently identify the model or models that provide the most accurate climate projections decades into the future. By considering the largest possible number of climate projections, analysts and decision makers can be better poised to identify “no regrets” approaches to adaptation, and less susceptible to unexpected manifestations of a changing climate (“no regrets” approaches in this context refer to strategies that will be effective in all possible climate futures). See Section 4.3 and Section 4.4.2 for more information on relationships among models and model evaluation.

In an ideal situation users would incorporate all available climate projections into their work. However, they are likely to be quickly confronted by practical constraints that limit the number of usable models for a given analysis or assessment. The most recent generation of downscaled climate projections are stored in several hundred individual files and require dozens of Terabytes (TB) of storage, in addition to the hundreds of hours needed to download the full set of projections. Time and resources needed for other related tasks such as data processing and communicating results also increase to likely infeasible levels if all available climate projections are considered. However, the impracticality of using *all* climate projections does not reduce the critical importance of considering as many projections as possible given a set of operational constraints. Users will need to strike an appropriate balance between:

- selecting **more** projections to better capture uncertainty and/or risk
- selecting **fewer** projections in the face of practical resource and logistics constraints

The LASSO tool helps users resolve this dilemma by providing a systematic, transparent, and logical process for selecting and, if desired, acquiring a subset of climate projections.

2.3 IDENTIFYING CLIMATE INFORMATION NEEDS

2.3.1 Climate Information in Decision Making

Analyses involving climate information are typically performed within a larger context of a decision-making process or are intended to inform future decision-making. Thus, the requirements and objectives of a specific management or policy decision should narrowly guide the process of identifying and selecting relevant climate information (Johnson and Weaver, 2009). Keeping this principle in mind can help analysts ensure they are gathering appropriate data while also helping them focus on obtaining only those data that will be relevant to the analysis.

The process of identifying and then incorporating climate information into an analysis requires several steps. The analyst should begin by considering the context of the decision: what are the underlying problems that the decision maker aims to address? The next step is to consider the role of future climate conditions within that context, allowing the analyst to begin considering what kind of information might be required (National Research Council, 2009). For some analyses, quantitative information about the future may not be necessary. For other applications, detailed high-resolution climate projections may be useful, and can serve as input to other models (such as hydrological models) that can simulate impacts such as changes in flood risk or infrastructure vulnerabilities (Kotamarthi et al., 2016; Moss et al., 2014).

Once an analyst understands the decision context, the next step in the process is to align climate information and decision needs. By considering the key elements that must be established in order to effectively inform a decision the analyst can ensure that inputs of climate data and subsequent outcomes from the analysis are relevant to the decision. This alignment is the focus of Section 2.3.2.

It is only when these initial steps of (i) establishing the decision context and (ii) identifying the climate information that is most relevant within that decision context are completed that one should move to the next step of obtaining climate information. Identifying decision needs is a critical step before selecting climate information, so an analyst should be prepared with this information before using the LASSO tool. This requires both identifying sources of information and determining what specific subset of those information sources to choose (Moss et al., 2014). This topic is the focus of Section 3, which outlines practical strategies for selecting climate information using the LASSO tool.

2.3.2 Identifying Information Relevant to Decision Context

To ensure climate information will be useful to the needs of decision makers, analysts will need to consider elements such as temporal resolution and the decision time horizon, spatial resolution, the decision maker’s tolerance for risk, and relevant climate variables. This section provides an overview of each of these key elements and describes how they relate to the needs of decision makers.

Climate variables: *Identifying relevant climate variables is an important step in acquiring climate information for decision making.*

The information required for climate variables, such as precipitation and temperature, depends strongly on the goals of the analysis and the assets or populations being studied. For example, decisions on design specifications for some types of infrastructure may be vulnerable to changes in mean seasonal precipitation, while other types of infrastructure (e.g., culverts) may be influenced by changes in extreme precipitation (Stainforth et al., 2007).

Many analyses require an understanding of future changes in the frequency, intensity, or duration of extreme events such as heat waves or extreme rainfall events. Higher model resolution does enable improved simulation of extreme events, although the accuracy of a model's projections does not necessarily increase linearly with increases in resolution (Flato et al., 2013).

The LASSO tool allows the user to select from a variety of precipitation and temperature variables and time frames. Some analyses will require information derived from the temperature and precipitation variables, such as streamflow or number of heatwaves; calculating derived variables is beyond the scope of the LASSO tool.

Temporal resolution and time horizon: *Information from climate models is available at different time intervals (e.g., daily, monthly) and for a variety of time horizons (e.g., mid-century, end-of-century). The chosen temporal resolution and time horizon of the climate information used in the analysis should be matched to the decision context and duration of influence of the decision.*

Information from climate models is often available at different temporal resolutions, from hourly to daily, monthly, seasonal, annual, or decadal. Hourly or daily information may be important for determining projections of extreme events (e.g., number of days above the historical 95% maximum temperature). Given natural variability in the climate system that can obscure climate trends when looking over short timescales, 30-year windows of climate model outputs may be combined to provide long-term averages (e.g., average temperature change for the period 2070–2099) as a best practice. In addition, to determine potential future change in climate conditions, users may compare modeled future conditions with modeled conditions that correspond to a historical baseline period (1981–2010 is a common historical baseline period to capture recent historical change). The decision context, including potential impacts due to thresholds in extreme events, should guide the choice of the temporal resolution and baseline historical period of climate information included in an analysis.

The duration of a decision's influence (e.g., the useful lifetime of planned infrastructure) and the frequency with which decisions need to be made are important factors to consider when choosing climate information for analysis (SERDP, 2016; National Research Council, 2009). For example, long-term infrastructure investments might require projections of relevant conditions spanning several decades or longer, while farmers, fisheries managers, and emergency managers would benefit from information on seasonal or inter-annual conditions (National Research Council, 2009; IPCC-TGICA, 2007). Figure 2 illustrates the varying time horizons for a range of activities; EPA's LASSO tool allows users to select data by season and for a variety of time horizons.

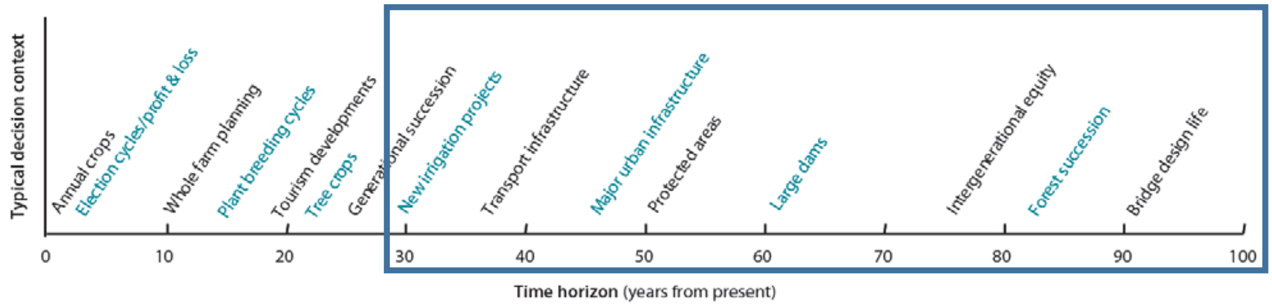

Figure 2. Decision contexts and associated time horizons

Box indicates the time horizons most applicable to the use of climate model information. Source: Lu, 2011

Spatial resolution: *Climate information is available at varying resolutions, but higher resolution does not necessarily mean more accurate information.*

Analysts working on local- or regional-scale assessments face the challenge of matching climate information to the spatial scale of the decision (National Research Council, 2009; National Research Council, 2010). Although climate projections typically focus on global or continental scales, most decision contexts require information on local areas.

General Circulation Models (GCMs) are mathematical models that simulate the physics, chemistry, and biology that influence the climate system (Walsh et al., 2014; Flato et al., 2013). These models approximate processes at the spatial scale that the model can resolve based on a combination of observations and scientific understanding (Walsh et al., 2014). Most GCMs divide the world into grid cells of about 60 to 100 miles per side and cannot simulate fine-scale changes at the regional level (Walsh et al., 2014), such as terrain (e.g., highly mountainous regions) and coastal environments that can influence climate features at a small scale (Kotamarthi et al., 2016). Because of this, a procedure known as downscaling is applied to translate GCM projections into higher-resolution information that can be used as input to local or regional impact analyses (Walsh et al., 2014); see Section 4.2 for more information on downscaling.

EPA's LASSO tool allows users to select climate information by EPA Region and source of statistically downscaled precipitation and temperature information. Several different sources of statistically downscaled data exist, such as Bias Corrected Spatially Downscaled (BCSD), Localized Constructed Analogs (LOCA), and Multivariate Adaptive Constructed Analogs (MACA). Each of these datasets are downscaled information from the Coupled Model Intercomparison Project (CMIP) 5 GCMs, and vary in the statistical techniques used, geographic coverage, and available variables. See Section 4 for additional information regarding statistical downscaling.

Risk tolerance: *A decision maker's risk tolerance may help determine which scenarios to include and what level of uncertainty is acceptable.*

Analysis to support effective climate-related decisions requires an assessment and understanding of risk and risk tolerance (Moss et al., 2014; Snover et al. 2013). Analysis can support risk management by using a range of climate scenarios and projections, informed by an understanding of their inherent uncertainties and limitations (National Research Council, 2009). As stated above, despite significant advances in our understanding of the climate system, important aspects of future climate remain difficult or even impossible to predict, and projections are thus subject to substantial uncertainties that must be accounted for in analyses. These include the inherent unpredictability about future climate forcings; necessitating assumptions about future conditions; variability within the climate system, on timescales of seasons to decades; and imperfect understanding of the response of the climate system to future forcing, meaning that no single climate model is able to provide "the answer" about future conditions (Hawkins and Sutton, 2009; see Section 4 for a more in-depth discussion of these and related issues).

In practical terms, this means that decision makers will need to deal with a range of future outcomes, as represented by the different projections from individual climate models. This range may, in turn, imply a broad range in the severity of the specific impacts most relevant for a given decision context, which the user must account for in the analysis, noting that even a range of GCM projections may not capture the full range of potential future conditions (Snover et al. 2013). For decision makers who are risk-averse, information on low-probability but high-consequence events, as well as scenarios of future climate that include "worst case" conditions, may be essential to include in the analysis. Where decision makers have a greater tolerance for risk, they may instead focus more attention on more moderate cases with a higher probability of occurrence or, alternatively, a range of future climate scenarios that include both "best case" and "worst case" outcomes to facilitate consideration of a wider range of potential solutions (SERDP, 2016). Selecting an even number of scenarios helps to avoid a common tendency to choose a middle scenario under the false assumption that it is the most likely scenario (Snover et al. 2016).

Transparency and open acknowledgement of uncertainty are key to informed climate-related decision making (National Research Council, 2009). While all projections of future conditions have an inherent degree of uncertainty, non-specialists may not fully understand the nature of uncertainty in climate projections. This may lead them to misperceive useful information as too unreliable to support action—or conversely to place too much confidence in projections (National Research Council, 2009). Uncertainty is inherent in nearly all decision making and should not preclude analysis of potential climate impacts that can inform action

(SERDP, 2016). The LASSO tool allows for a variety of selection strategies to accommodate a range of tolerance to risk and uncertainty. It allows users to more easily harness the collective wisdom of the existing suite of state-of-the-art climate models for their region, system, and decision context.

3. EPA'S LASSO TOOL: A PRACTICAL APPROACH TO SELECTING CLIMATE PROJECTIONS

- **Scatterplots are helpful visual devices that aid in the scenario selection process**
- **The LASSO tool can be used to apply selection strategies to scatterplots and obtain a subset of raw climate data for use in analyses**

3.1 PURPOSE OF EPA'S LASSO TOOL

As described above, the LASSO tool helps users select climate projections from groups of models for use in decision making, impact analyses, and vulnerability assessments, given a user's specific needs and decision context. LASSO represents an approach designed to be sufficient for immediate needs and goals while not guaranteed to be optimal or perfect. The output of the tool is a subset of raw climate projection data and figures based on the user-specified study area, scenarios, and climate variables, as well as the chosen selection strategy. LASSO addresses the deceivingly complex question "*which climate projections should I use?*" by disaggregating the problem into discrete, logical steps.

3.2 SELECTING CLIMATE PROJECTIONS

The LASSO tool guides users through a process of six steps:

1. **Define the study area** – pick one of 10 EPA Regions or one of the lower 48 states or the District of Columbia
2. **Select a data source** – both the BCSD and LOCA datasets are available
3. **Select a pathway** – RCP 4.5 and RCP 8.5 appear most frequently in impact studies
4. **Climate variables** – Two combinations of variable (temperature, precipitation), season (annual, winter, spring, summer, fall), and time period (2021-2050, 2041-2070, 2070-2099) must be selected to form the axes of the LASSO scatterplot
5. **Selection strategies** – One or more approaches for identifying a subset of climate projections
6. **Download your results** – Users have the option to immediately download spatial data, maps, and scatterplot graphics, or use an interactive scatterplot widget to explore other data sources, scenarios, etc.

Viewing climate model projections in two dimensions provides an effective way to evaluate their range and variety. Two-dimensional scatterplots are familiar to a broad, interdisciplinary audience, are generally easy to interpret, and provide a simple, concise visual reference as compared to other diagrams or figures representing three or more dimensions of information. Furthermore, downscaled climate projections frequently include only temperature and precipitation measures[1], in which case two-dimensional summaries are an appropriate choice. Scatterplots lend themselves to quadrant-based groupings or typologies, such as “cool and wet” or “hot and dry”. These descriptive typologies are useful in that they not only capture the hydrological gradient and distinct sets of impacts, but they are also intuitive and easily communicated to a broad audience.

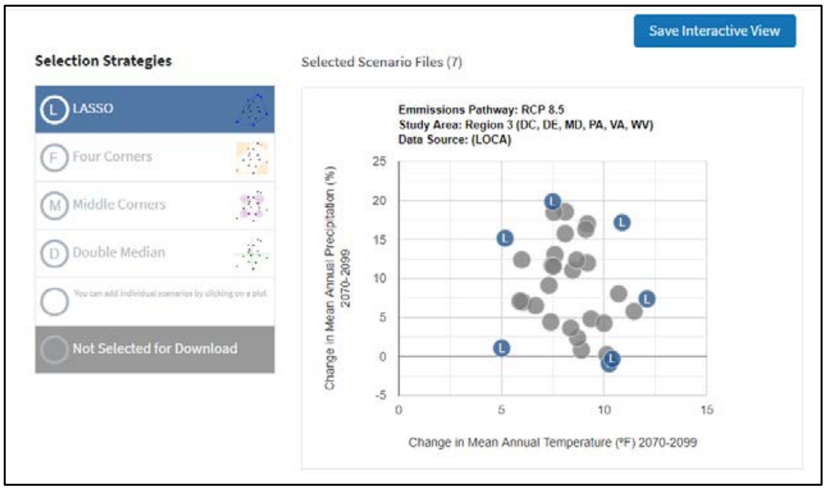

Figure 3. Users of the LASSO tool have the option to customize results using an interactive scatterplot to select climate projections

In this approach, the tool presents climate projections, based on the x- and y-axis parameters chosen by the user, on a scatterplot. The user can then select a subset of these projections for use (see Section 2.2) using one of the selection strategies discussed in Section 3.3.

3.3 SELECTION STRATEGIES IN THE LASSO TOOL

In developing a climate analysis for a location or project, an analyst may be confronted with a large universe of future climate projections. For example, selecting the four RCPs and the more than 40 downscaled CMIP5 climate models can result more than 150 unique projections.

The selection strategies discussed below help the user quickly and easily identify a subset of projections, shown in scatterplots generated by the LASSO tool, that bound the range of a larger group of climate projections in two dimensions (such as air temperature and precipitation) simultaneously. At a high level, the selection strategies work by calculating and plotting change statistics of all the climate models in a two-dimensional space, then selecting specific projections based on their geometric position in the resulting scatterplot. This general approach allows for

[1] There has been a recent trend of downscaling efforts that include several additional climate variables, such as relative humidity and wind speed.

the efficient selection of representative ensemble members that describes a range of possible future change in a systematic way that is also logically desirable to the user.

Table 1 lists and compares the selection strategies (described in the sections below) that can be used in the LASSO tool.

Table 1. Summary of scenario selection strategies

Strategy	Advantage	Disadvantage
Lasso	Captures the full envelope of potential change described by the climate models	Typically results in ~8-10 models; time and resource requirements potentially very high
Four Corners	Fewer models than the Lasso strategy means less time and fewer resources; still captures a broad range of potential futures	Could miss the minimum or maximum of each axis
Middle Corners	Ignores projections that might be considered outliers; captures a range of values without a perceived focus on extreme outcomes	Disregarding extreme projections may confer some risk; gives the impression that selected projections represent more likely futures
Double Median	Lowest relative need of time and resources; central projections of change may be useful in some contexts	Easily misinterpreted as the "most likely" or "best" scenario; information about unexpected or extreme changes is completely absent

3.3.1 Lasso

The lasso strategy works by identifying the set of points in the LASSO scatterplot that make up an imaginary "envelope" around all other points. This boundary polygon is also referred to as the *convex hull* and, in the context of LASSO, can be used to capture the full range of changes projected by a group of climate models. Similar approaches have been suggested or even used by others to identify a subset of climate projections for impact studies (Cannon, 2015; Salathé, 2007; Stainforth, 2007). This selection method will necessarily capture the minimum and maximum values for each variable but will also include other projections that provide additional information about potential combinations of change. Of the selection approaches presented in this report, the Lasso strategy corresponds to the *lowest* risk tolerance, i.e., the largest amount of information is included. A disadvantage to this strategy is that incorporating the resulting information into an analysis may require a larger amount of time and resources. See Figure 4. Black dots denote individual climate projections and red circles indicate those models selected by the *Lasso* strategy.

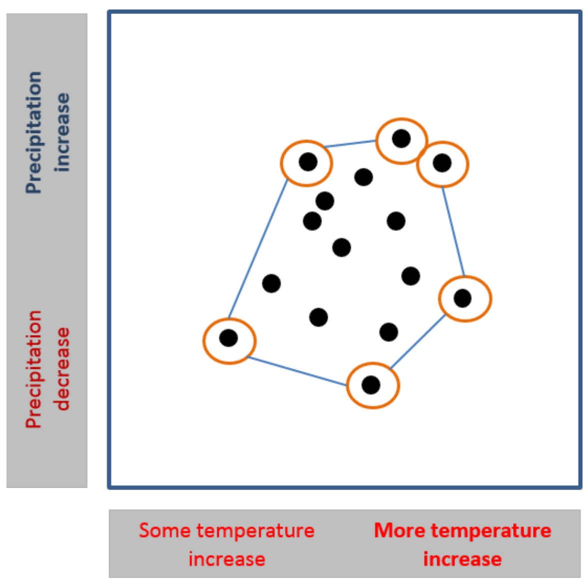

Figure 4. Illustrating the *Lasso* selection strategy. Black dots denote individual climate projections. Red circles indicate models selected by the *Lasso* strategy.

3.3.2 Four Corners

The *Four Corners* strategy captures a broad range of potential climate futures by choosing a representative projection from each of four hypothetical quadrants. An imaginary bounding box can be drawn around the scatterplot values and selecting the model that is closest (in Euclidean distance) to each of the four corners of this box yields a subset that maximizes differences among four projections. This approach has been used widely in climate studies to identify a useful subset of climate change projections (e.g., Hosseinizadeh et al., 2015). This strategy captures a limited number of projections compared to the *Lasso* approach, likely reducing the amount of time and resources needed to process, analyze, or summarize the range of information. However, this technique risks missing the minimum or maximum projections on either axis, as demonstrated by the unselected black dots lying on the dotted line in Figure 5.

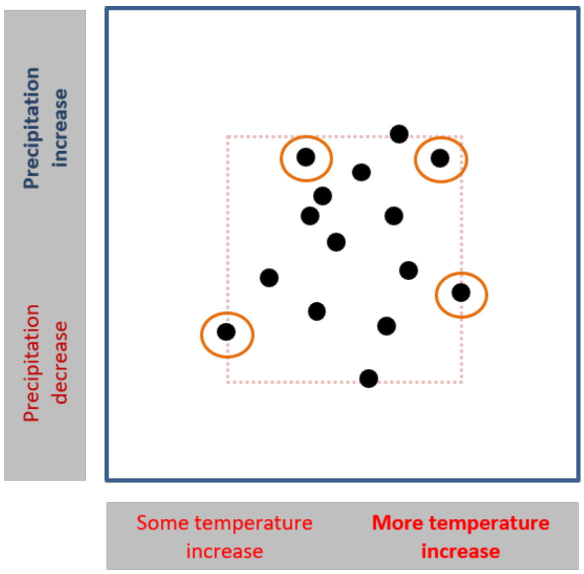

Figure 5. Illustrating the *Four Corners* selection strategy. Black dots denote individual climate projections. Red circles indicate models selected by the *Four Corners* strategy. Dotted lines are drawn at the minimum and maximum projected values for each axis.

3.3.3 Middle Corners

The *Middle Corners* selection strategy is similar to the *Four Corners* approach in that the goal is to identify a projection from each of four quadrants. However, the *Middle Corners* strategy uses the 25th and 75th percentiles of each axis to identify the corners of an imaginary box. The Bureau of Reclamation (2015) used a nearly identical approach to identify climate projections for an assessment of risk in the western U.S. This strategy is less likely to include model results that might be considered outliers, however this strategy will also disregard the most extreme projections of change where exposure and vulnerability may reach levels of concern. Note the relatively tight grouping of selected projections in Figure 6.

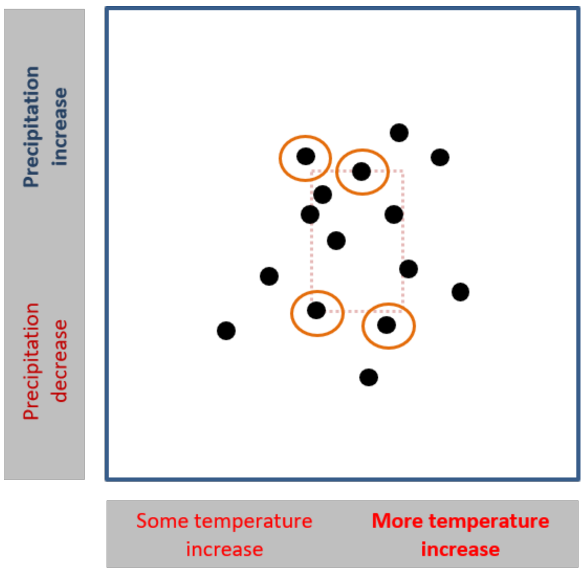

Figure 6. Illustrating the *Middle Corners* selection strategy. Black dots denote individual climate projections. Red circles indicate models selected by the *Middle Corners* strategy. Dotted lines are drawn at the 25th and 75th percentile projected values for each axis.

3.3.4 Double Median

The *Double Median* strategy identifies a single projection by minimizing the Euclidean distance from a point at the intersection of the median value of each axis. This approach is useful when a central projection is needed, for example, to avoid the perception that results are only representative of extremes. This central estimate may also be combined with other selection strategies, such as *Four Corners* (Hosseinizadeh et al., 2015). Including a central estimate of change may facilitate a path toward consensus or provide a useful benchmark when comparing impacts under multiple scenarios of climate change. However, great care must be taken to avoid suggestions that the *Double Median* strategy is the "best" projection or "most likely" outcome. Note the wide range of potential future change that is not at all captured by the single, central projection selected in Figure 7.

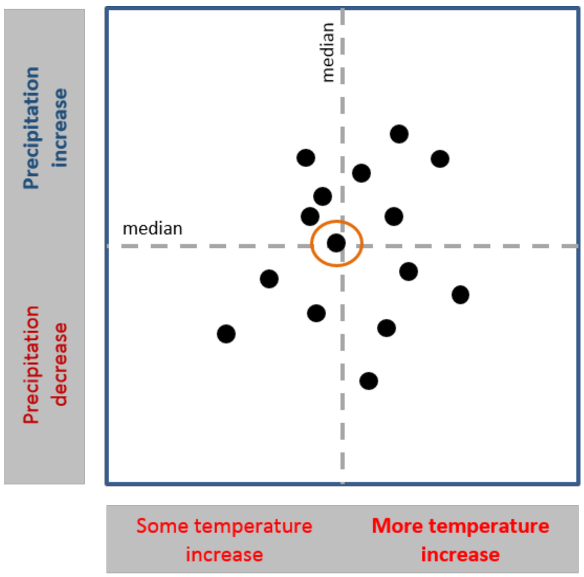

Figure 7. Illustrating the *Double Median* selection strategy. Black dots denote individual climate projections. Red circles indicate the model selected by the *Double Median* strategy. Dashed lines are drawn at the median projected values for each axis.

3.4 OUTPUTS FROM THE LASSO TOOL

After users have selected climate scenario information, the LASSO tool provides the ability to download raw climate projection data based on the user-specified study area, scenarios, and climate variables. In addition, users can download static map images of the climate scenario information for the specified study area. Refer to Section 5 for examples of LASSO outputs. Interested users can find additional details regarding downloadable data within the tool; download functions may change over time. As noted above, users should be aware that there are uncertainties with any climate projections that cannot be fully accounted for in future climate impact studies. Approaches for dealing with these intractable uncertainties are beyond the scope of this report.

3.5 CURRENT LIMITATIONS OF THE PROCESS AND TOOL

The LASSO tool and the approaches to using it described above include some limitations and caveats. Using the tool requires some familiarity with best practices in matching climate information to decision needs, as well as an understanding of how to use climate information accurately and appropriately. For example, a user might select a too-limited subset of data using the LASSO tool, unknowingly introducing large uncertainty.

Examples of Related Climate-Data Tools

Several available tools provide access to climate data, although they may be difficult to apply in decision-making. For example, they cannot be used to download geographic information system-ready data, provide only limited guidance on what data to use, or present only spatially and temporally constrained summaries.

U.S. Global Change Research Program Climate Explorer: Offers graphs, maps, and data of observed and projected temperature, precipitation, and related climate variables for every county in the contiguous United States. Web page: https://crt-climate-explorer.nemac.org/.

U.S. Geological Survey National Climate Change Viewer: Includes the historical and future climate projections from 30 of the downscaled models for two of the RCP emission scenarios (4.5 and 8.5). Allows users to visualize projected changes in climate (maximum and minimum air temperature and precipitation) and the water balance (snow water equivalent, runoff, soil water storage and evaporative deficit) for any state, county and United States Geological Survey Hydrologic Units. Web page: https://www2.usgs.gov/landresources/lcs/nccv.asp.

NCAR/GIS Program Climate Change Scenarios Data Portal: offers shapefiles, text files, and images of climate change projections. Many 2D variables from modeled projected climate are available for the atmosphere and land sector. Web page: http://gisclimatechange.ucar.edu/.

US. Geological Survey Geo Data Portal: provides access to numerous datasets, including gridded data for climate and land use. Web page: https://cida.usgs.gov/gdp/.

The LASSO tool provides basic functionality for selecting projections. The tool currently uses a historical baseline of 1981–2010. Future versions of the tool may add additional functionality and data, such as the ability of the user to directly select a custom group of projections, access to additional downscaled climate model data archives, or additional climate variables.

4. BACKGROUND ON SCENARIOS, MODELS, AND SELECTION CRITERIA

- **Climate scenarios are used to explore a range of potential future climate conditions and levels of impact**
- **Downscaling techniques are usually applied in order to generate higher-resolution information, which may be appropriate as an input to local or regional analyses**
- **Decisions can more completely capture the range of possibilities by using results of multiple models running multiple scenarios**
- **Because of the large number of sources and types of climate projections available, using selection criteria to narrow the number of projections can be helpful in simplifying the selection process**

This section contains additional information on scenarios, models, and selection criteria and is intended for readers interested in more technical information and context.

4.1 CLIMATE SCENARIOS

Climate modelers use GCMs to project the Earth's future climate under a range of scenarios. In most cases these scenarios were adopted by the Intergovernmental Panel on Climate Change (IPCC) for the Fifth Assessment Report (2013), or an earlier set of scenarios from the IPCC's Fourth Assessment Report (2007).

Scenarios represent a significant, but necessary, source of uncertainty and risk in climate projections. If only a worst-case scenario is considered, there is a risk of incurring unnecessary costs (e.g., through over-engineering). In contrast, assuming only an optimistic scenario runs the risk of costly damages if future conditions turn out to be far less favorable. When looking at relatively long-term climate conditions (i.e., end of 21st century), model selection and the choice of scenario are the key sources of uncertainty (Hawkins and Sutton, 2009) and should reflect the risk tolerance of the decision maker (SERDP, 2016).

4.2 DOWNSCALED CLIMATE INFORMATION

As discussed in Section 2.3, climate projections are generally produced at a relatively coarse spatial resolution, whereas most decision contexts require highly localized climate information. Downscaling can be applied to translate GCM projections into higher-resolution information, which may be appropriate as an input to local or regional impact analyses (Walsh et al., 2014). There are two types of models commonly used for downscaling: dynamical and statistical. Both rely on inputs from GCMs.

Dynamical downscaling models, often referred to as regional climate models (RCMs) (Walsh et al., 2014), use outputs from a GCM as boundary conditions to drive a separate higher-resolution model over a limited spatial domain that better represents local or regional physical processes (Kotamarthi et al., 2016; Flato et al., 2013). These models are very computationally intensive.

Statistical downscaling models use observed relationships between large-scale weather features and local climate to statistically translate projections from GCMs down to a finer scale (Walsh et al., 2014; Flato et al., 2013; Lu, 2011). Statistical downscaling models are best suited for analyses requiring a range of future projections that reflect the uncertainty in scenarios and climate sensitivity, at the scale of observations that may already be used for planning purposes (Walsh et al., 2014).

Climate models do not perfectly simulate historical conditions and raw model output may have systematic differences, or biases, between a simulated climate statistic and the corresponding real-world climate statistic (Maraun 2016). For example, some models may have a general bias toward warmer conditions than recorded in the historical observed record; other models may generally show wetter conditions when compared with the historical data. To address these biases, it is now a standard practice to “bias-correct” downscaled datasets for impact modeling using techniques such as multiple linear regression, quantile mapping, or the delta change approach (Maraun 2016) to better align with the observed conditions.

RCMs can directly simulate the response of regional climate processes to global change and are not reliant on the statistical patterns from the past holding in the future, while statistical models can better remove any biases in simulations relative to observations. Ideally, climate impact studies could use both statistical and dynamical downscaling methods, but this coupled approach is very resource-intensive (Walsh et al., 2014).

4.3 MODEL INTERDEPENDENCE AND PERFORMANCE

In addition to considering multiple scenarios, decisions can more completely capture the range of possibilities by using results of multiple models running multiple scenarios. Using a single model run is not considered scientifically rigorous because different GCMs often produce different results, and there is no consensus that any one model is comprehensively better or more accurate than others.

Models introduce additional sources of uncertainty (in addition to the uncertainties related to future climate forcings), such as scientific uncertainty about the climate system and its sensitivity (Kotamarthi et al., 2016). Natural climate variability, including the climate system’s inherent randomness, plays an especially important role in uncertainty over short timescales (10-20 years) (SERDP, 2016; Walsh et al., 2014; Flato et al., 2013). For longer timescales (mid to late century), using information from multiple climate models and scenarios can capture the range of possible outcomes and uncertainties (SERDP, 2016; Flato et al., 2013). Considering the full range of outputs from models, rather than their average or median values, provides a more accurate representation of uncertainty, although low-probability, high-consequence future conditions may still fall outside of the full model set.

GCMs are frequently updated or otherwise revised using code that worked well in previous iterations. Additionally, code for modules and routines is frequently shared within the modeling community, allowing revisions to be completed with more community participation while requiring less time for development and implementation. Specifically, many of the GCMs used in CMIP5 are models that have been revised or updated from previous versions over the last two decades. Many of these come from the same modeling center or share some of the same underlying code. The strengths and weaknesses of particular models can thus be passed on to newer model versions and to other models through the exchange of code and ideas.

The relationships among models is often hard to distinguish when models are titled differently or appear from unrelated modeling centers. The use of related models can lead to an unrealistically small spread in projections, resulting in a bias toward an artificial consensus in model predictions. While excluding some models from an ensemble may be necessary given technical or computational challenges, special attention should be paid to down-weighting models that have very similar controls or a shared lineage in order to avoid this kind of convergence bias.

Pennell and Reichler (2011) developed a statistical analysis to evaluate interdependences among ensemble members in CMIP3. In Figure 8, the grey column indicates the effective number of models based on the correlation of the error structure determined for each model. Pennell and Reichler (2011) argue that this demonstrates that the CMIP3 group is “not a very diverse ensemble” given the low number of independent models, even though the large number of models in CMIP3 gives the opposite impression. Analysts should keep these interdependencies in mind when selecting projections: a too-limited set of projections from related models may introduce unexpected biases.

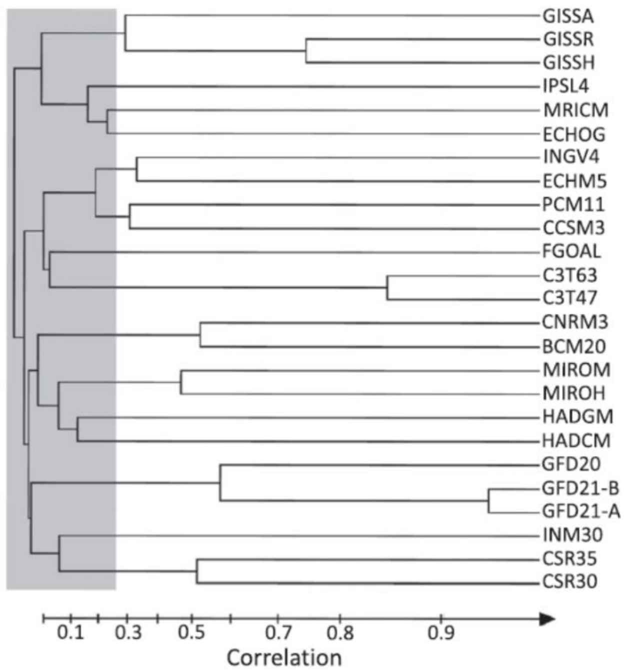

Figure 8. Effective number of models from CMIP3 based on statistical analysis of effective degrees of freedom or effective sample size from a given dataset. The correlation values are calculated based on model error structure.

Source: Pennell and Reichler, 2011

4.4 STRATEGIES FOR SELECTING PROJECTIONS

4.4.1 Overview of Selection Criteria

Because of the large number of sources and types of climate projections available, using selection criteria to narrow the number of projections can be helpful in the selection process. Climate model research groups and the CMIP process commonly address some of the criteria, including:

- *Consistency with global projections:* Projections should be consistent with a broad range of global warming projections based on alternative scenarios of climate forcing (IPCC-TGICA, 2007). The IPCC serves as a source of reference for the range of global warming projections.

- *Physical plausibility:* Projections should be physically plausible within the basic laws of physics, and the combination of changes in different variables should be physically consistent (IPCC-TGICA, 2007).

A variety of additional criteria are important to selecting projections, which are relevant to the information needed by the user to implement the LASSO tool and supported by the LASSO tool's practical approach. Potential additional selection criteria to consider include the following:

- *Applicability in impact assessments:* Projections should describe changes in a sufficient number of variables on a spatial and temporal scale that allows for impact assessment. For example, impact models may require input data on variables such as precipitation, humidity, and wind speed at spatial scales ranging from global to site-specific and at temporal scales ranging from annual means to daily or hourly values (IPCC-TGICA, 2007). Currently, the LASSO tool provides information only on changes in mean annual temperature and changes in mean annual precipitation for the United States. Users can view and download information at the EPA Region level.

- *Representativeness:* Projections should be representative of the potential range of future regional change in order to estimate a realistic range of possible impacts (IPCC-TGICA, 2007). Applying the results of more than one GCM in an impact assessment provides a range of representative results. GCMs can differ widely from each other in their estimates of regional changes, especially for variables such as precipitation, where some models may project wetter conditions in a region while others project drier conditions. The LASSO tool facilitates selecting a practical set of results from more than one GCM.

- *Accessibility:* Scenarios used in projections should be straightforward to obtain, interpret, and apply (IPCC-TGICA, 2007); the LASSO tool helps to directly support accessibility.

- *Vintage:* Recent model simulations are likely to be more reliable than those of an earlier vintage. They are based on recent knowledge, incorporate more processes and feedbacks, and usually have a higher spatial resolution than earlier models (IPCC, 2001). LASSO relies on recent model simulations (i.e., CMIP5).

- *Resolution:* As climate models have evolved and computing power has grown, their resolution has tended to increase. Some of the early GCMs operated on a horizontal resolution of some 1,000 km with between 2 and 10 levels in the vertical. More recent models run closer to a spatial resolution of 250 km with approximately 20 vertical levels. Although higher-resolution models contain more spatial detail, this does not necessarily guarantee superior performance (IPCC, 2001). The LASSO tool provides access to statistically downscaled data at approximately 4-6 km grid cell resolution.

- *Validity:* Analysists should use data from GCMs that simulate the present-day climate most faithfully, on the premise that these GCMs should also yield the most reliable representation of future climate. This approach involves comparing GCM simulations that represent present-day conditions with the observed climate (IPCC, 2001). The LASSO tool does not directly compare simulations with observed climate, but many downscaled climate data sources are corrected for systematic biases.

4.4.2 Finding the "Best" Model(s)

Evaluations of climate model projections are based on the ability to faithfully simulate the past; future skill is unknowable. There is thus no objective standard for what constitutes “good” or “good enough,” because there is no way to know in advance how accurately any model simulates future conditions. Furthermore, because the most appropriate climate inputs for any given application depend on the nature of both risk tolerance and associated vulnerabilities, there is no prescriptive guidance for the “best” climate models, methods, or projections to use in any situation (Kotamarthi et al., 2016). Any determination of the best or most appropriate model(s) would be specific to a time period, geographic area, and numerous other qualifications. The process for selecting, obtaining, and incorporating climate data into decisions can be time-consuming, and high levels of technical skill and knowledge are required. In the end, however, conclusions drawn from climate projections are still subjective, reflecting the scope of the information included in the analysis or assessment.

Mendilk and Gobiet (2015) describe a statistical, quantitative methodology to enable selection of a representative set of models from the ensemble while still maintaining the essential characteristics of the ensemble. First, an analysis is completed among the climate variables to establish patterns of change within the multi-model ensemble. Second, a cluster analysis, focusing on models with similar simulations, is performed to isolate these multivariate patterns. Third, a sampling method is introduced to gather a single representative model from each cluster. Mendilk and Gobiet’s (2015) analysis was able to reduce an ensemble from 25 models to 5 for a given example. However, such a methodology is time-intensive to implement and perform, potentially making it impractical for a time- or resource-constrained analysis.

Together, these facts suggest that a heuristic (i.e., imperfect but “good enough”) approach may be preferable and certainly more practical than trying to identify a single or small group of ideal models for the particular analysis at hand. LASSO offers this type of approach to problem-solving: its outputs are sufficient for immediate needs and goals while not guaranteed to be “optimal” or “perfect.”

5. LASSO SCATTERPLOTS FOR EPA REGIONS

- **The following scatterplots describe a range of potential climate change for EPA regions across a small, but generally informative subset of possible climate variables and time horizons.**
- **These scatterplots describe the average annual change in temperature on the horizonal axes (Fahrenheit) and change in precipitation (%) on the vertical axes.**
- **Values shown are the difference between the 2070-2099 future period and 1981-2010 historical period.**
- **Model realizations that correspond to the 'Lasso' selection strategy are identified; other projections are shown as gray dots.**

5.1 REGION 1

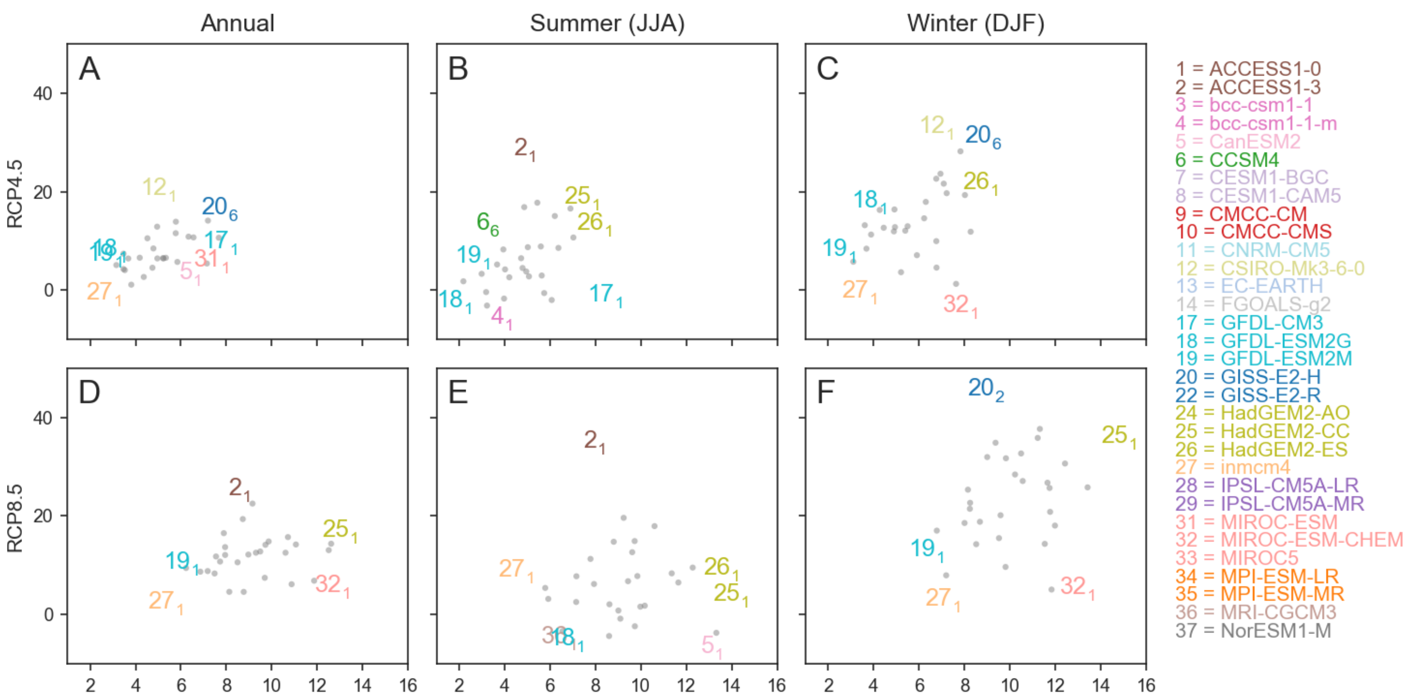

Figure 9. LASSO scatterplots for EPA Region 1, excluding Puerto Rico and the Virgin Islands.

5.2 REGION 2

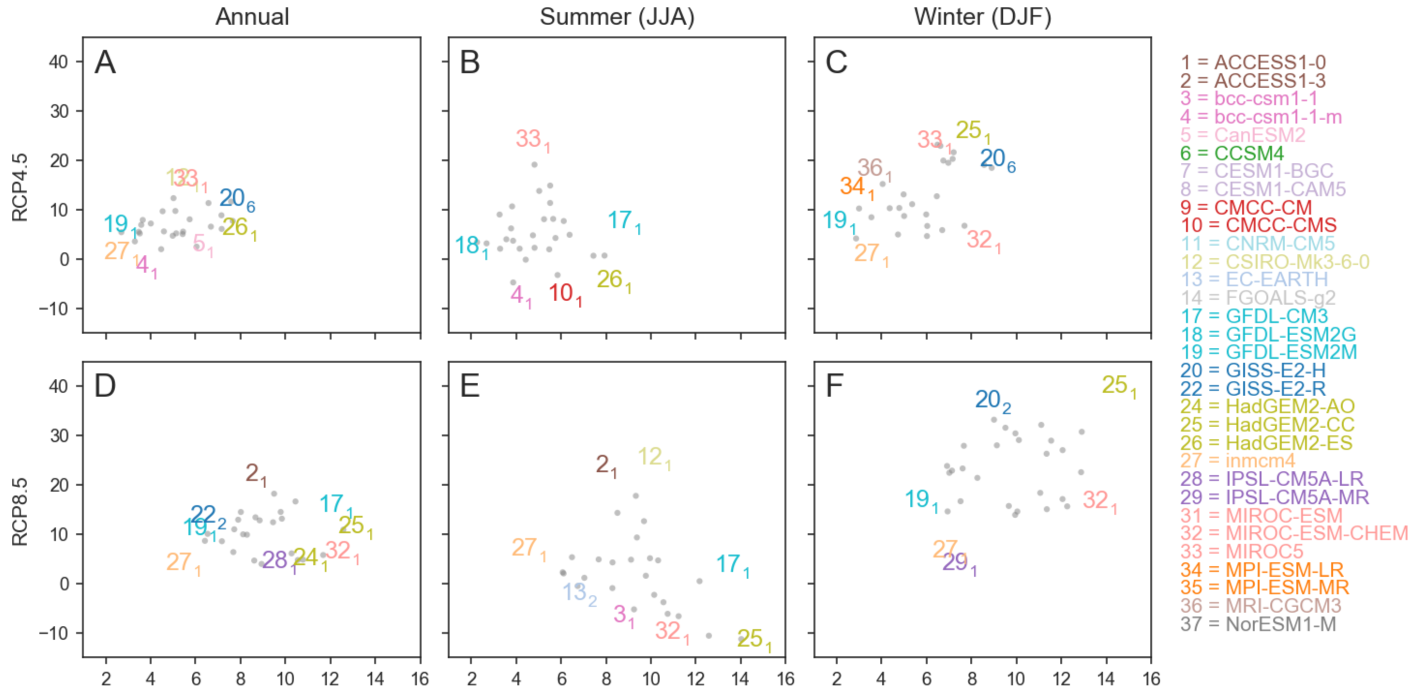

Figure 10. LASSO scatterplots for EPA Region 2.

5.3 REGION 3

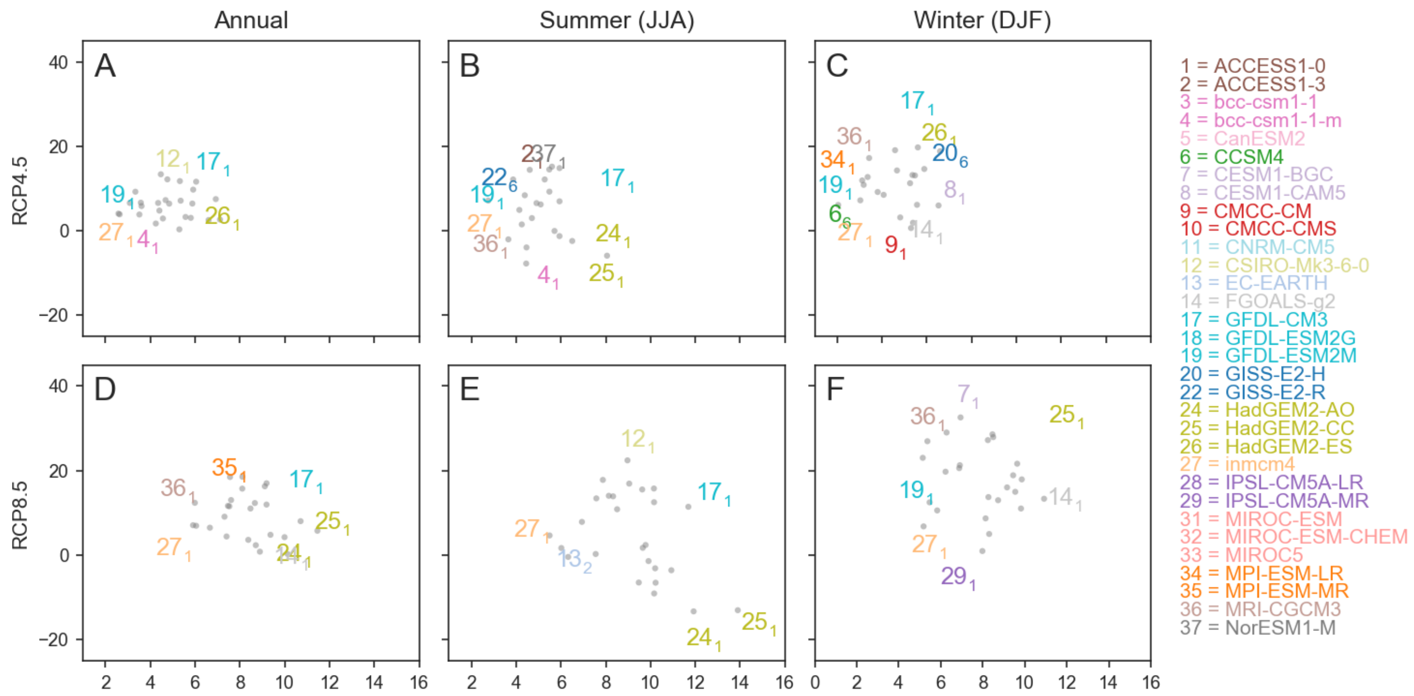

Figure 11. LASSO scatterplots for EPA Region 3.

5.4 REGION 4

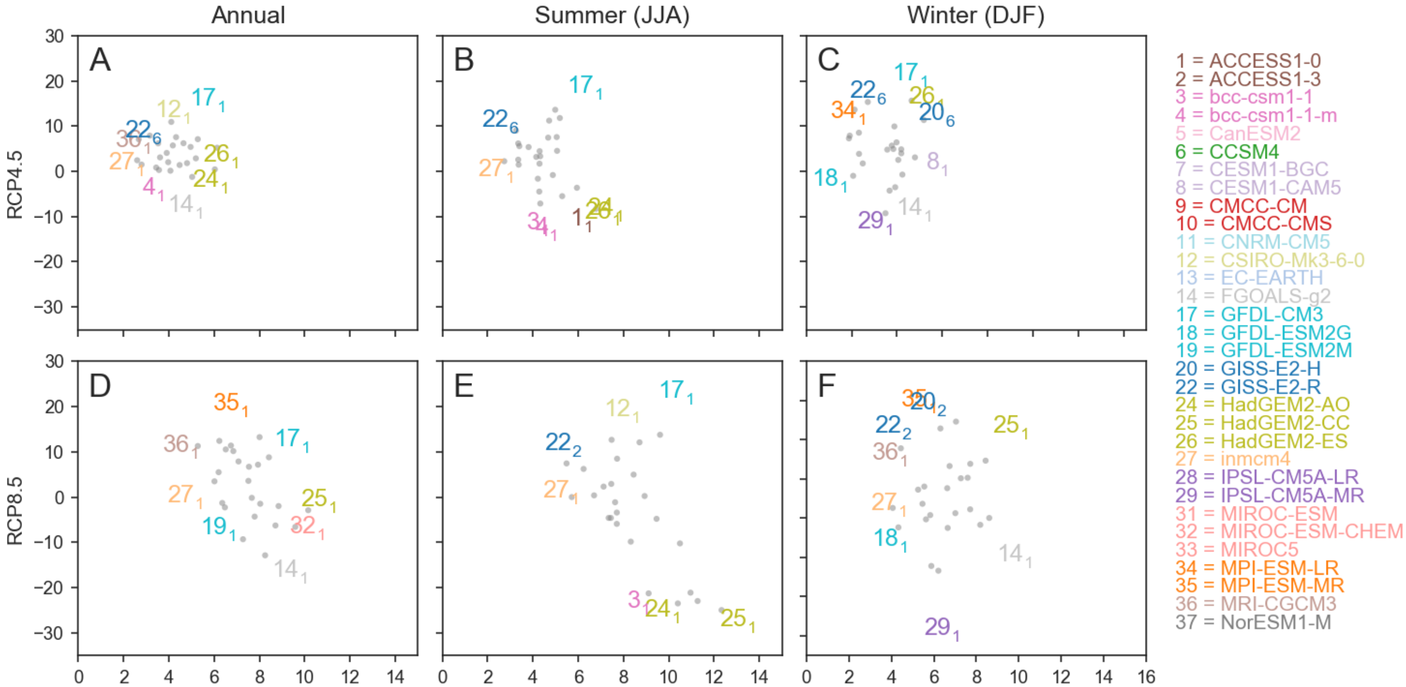

Figure 12. LASSO scatterplots for EPA Region 4.

5.5 REGION 5

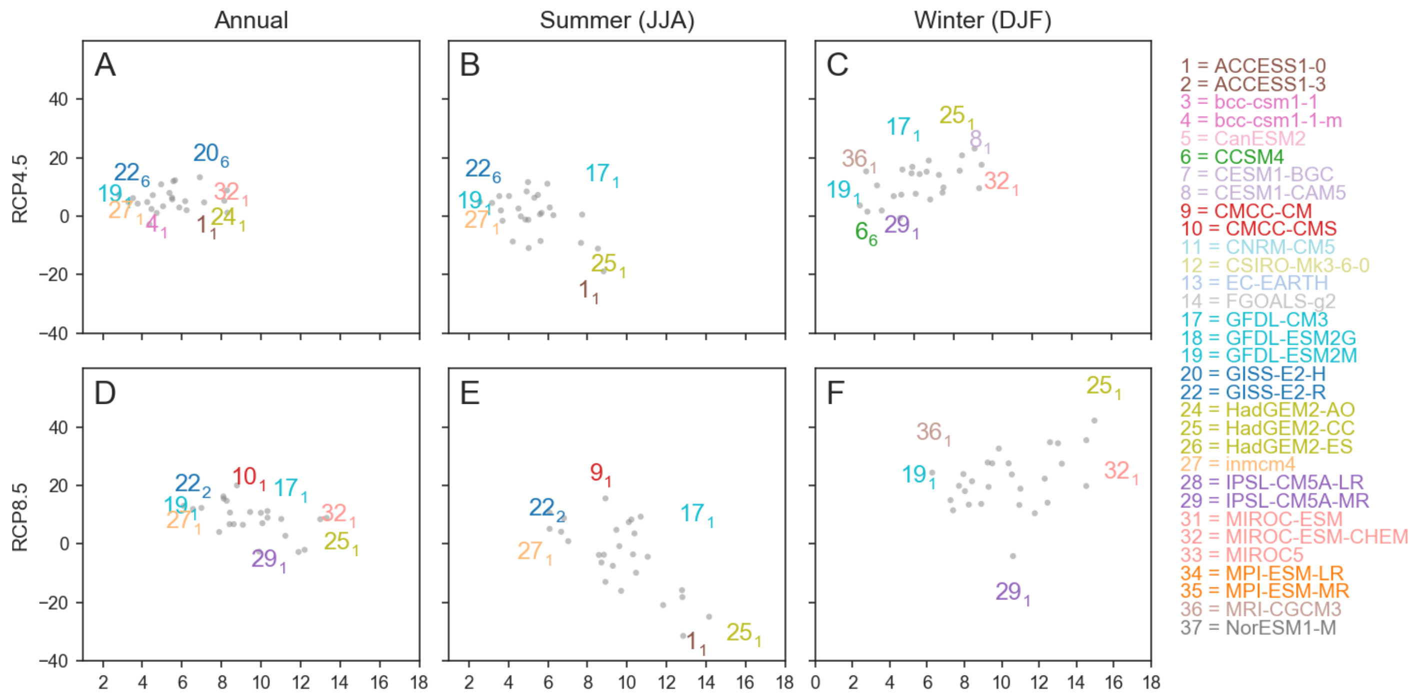

Figure 13. LASSO scatterplots for EPA Region 5.

5.6 REGION 6

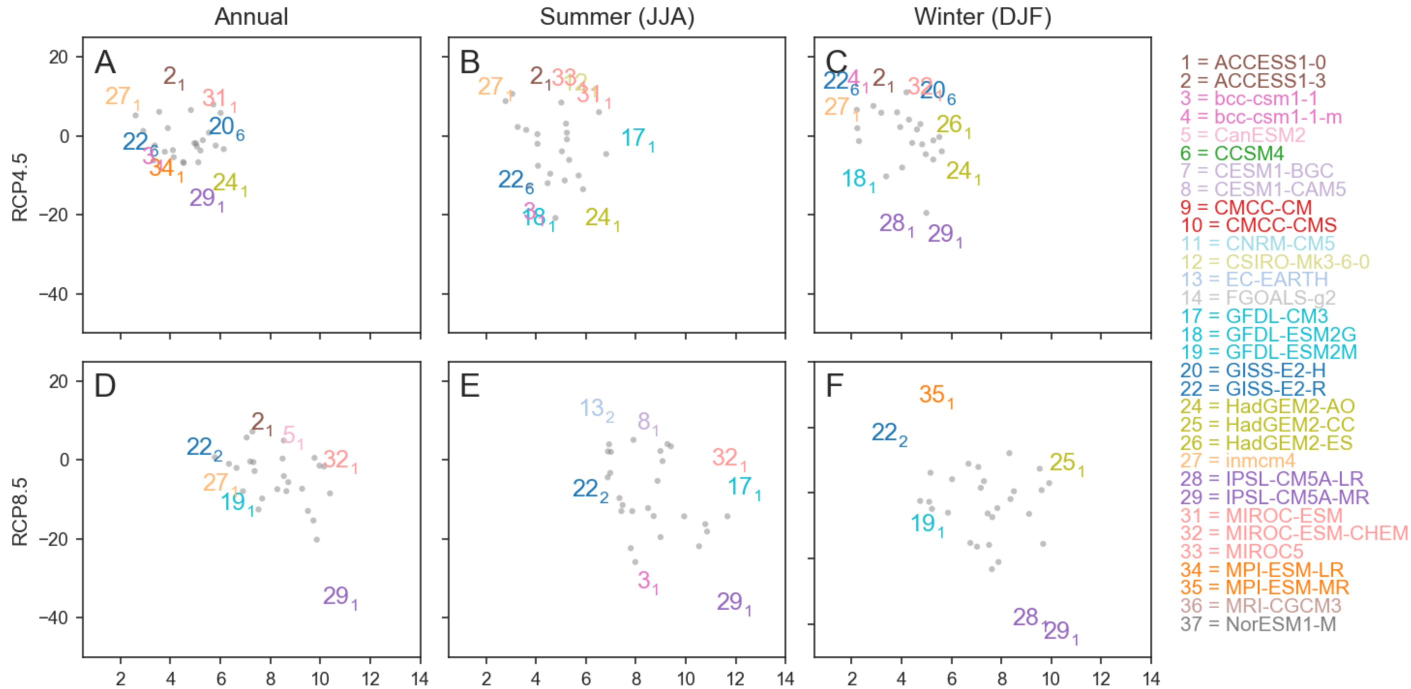

Figure 14. LASSO scatterplots for EPA Region 6.

5.7 REGION 7

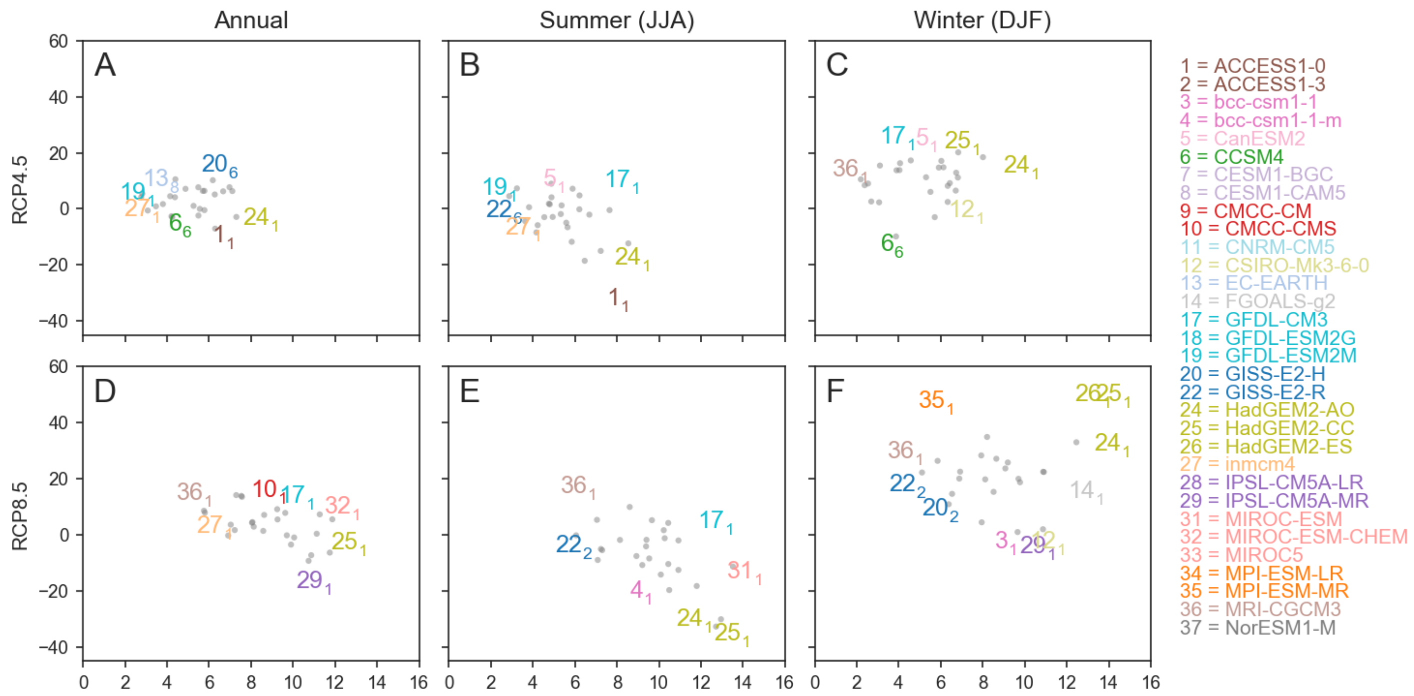

Figure 15. LASSO scatterplots for EPA Region 7.

5.8 REGION 8

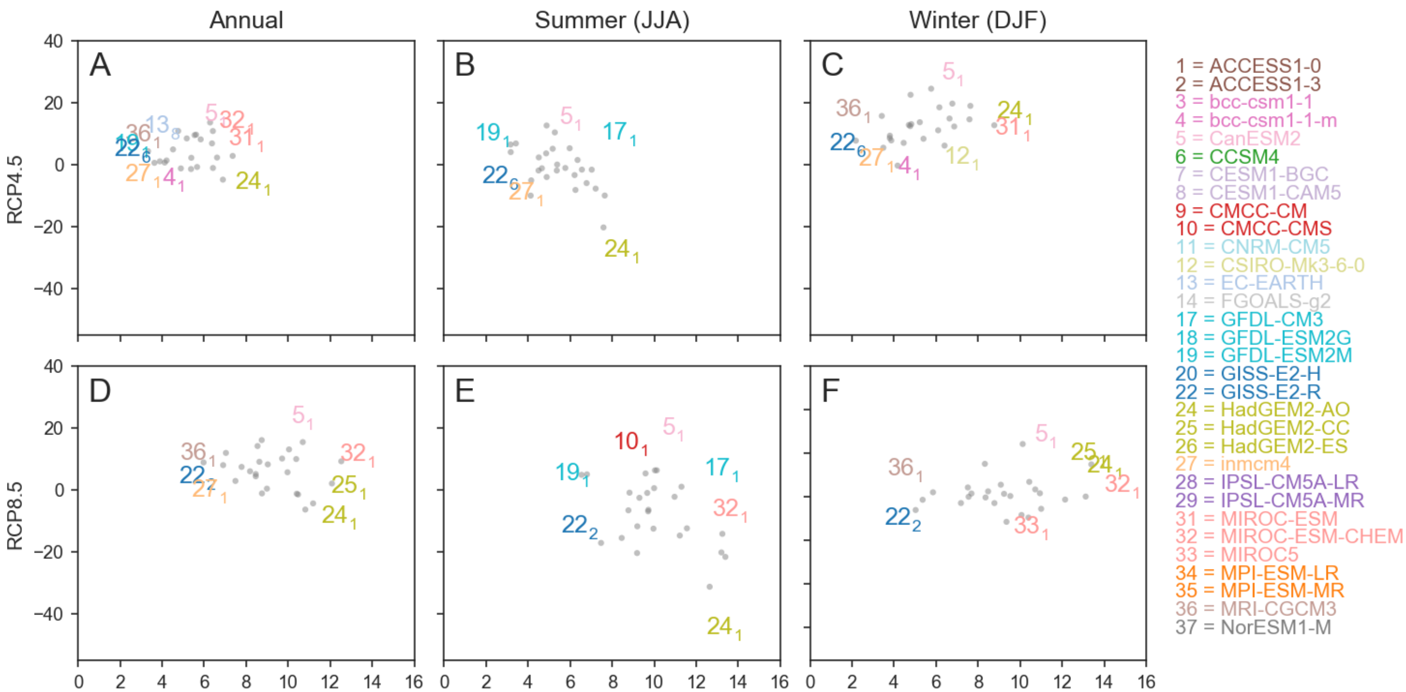

Figure 16. LASSO scatterplots for EPA Region 8.

5.9 REGION 9

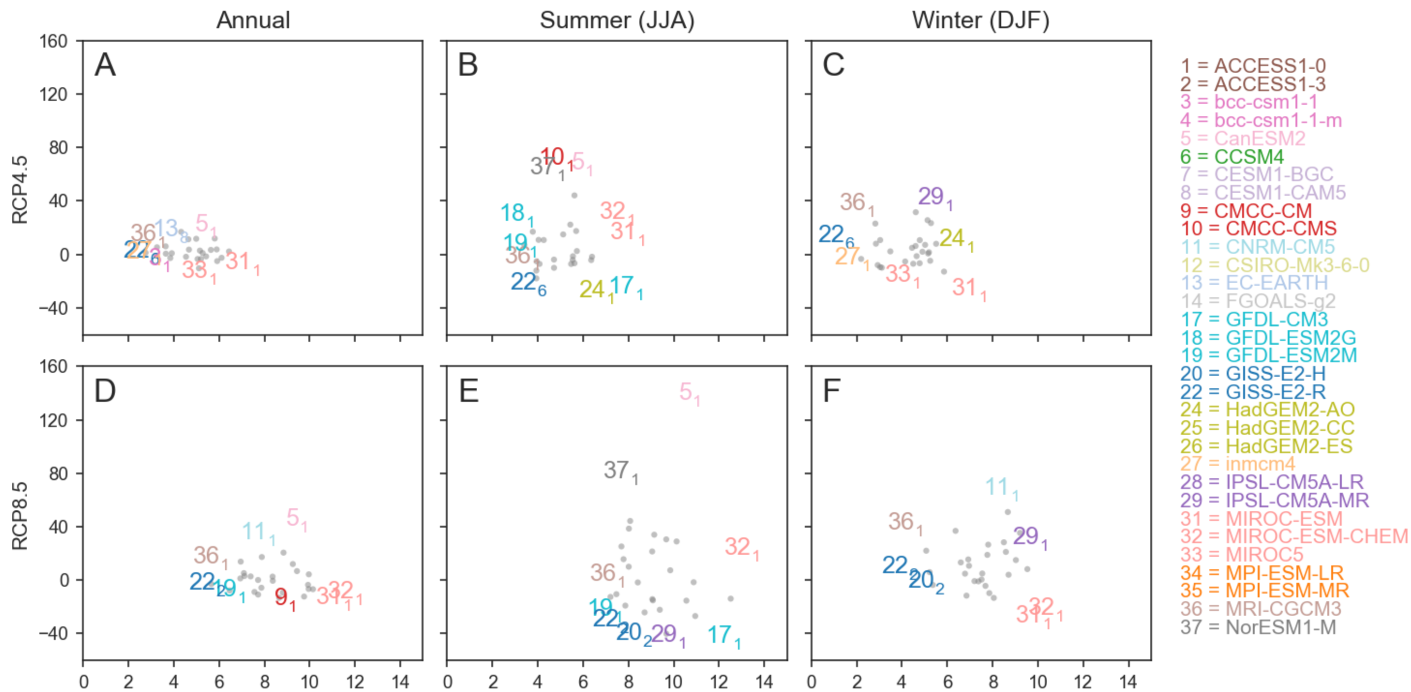

Figure 17. LASSO scatterplots for EPA Region 9, excluding Hawaii and island territories.

5.10 REGION 10

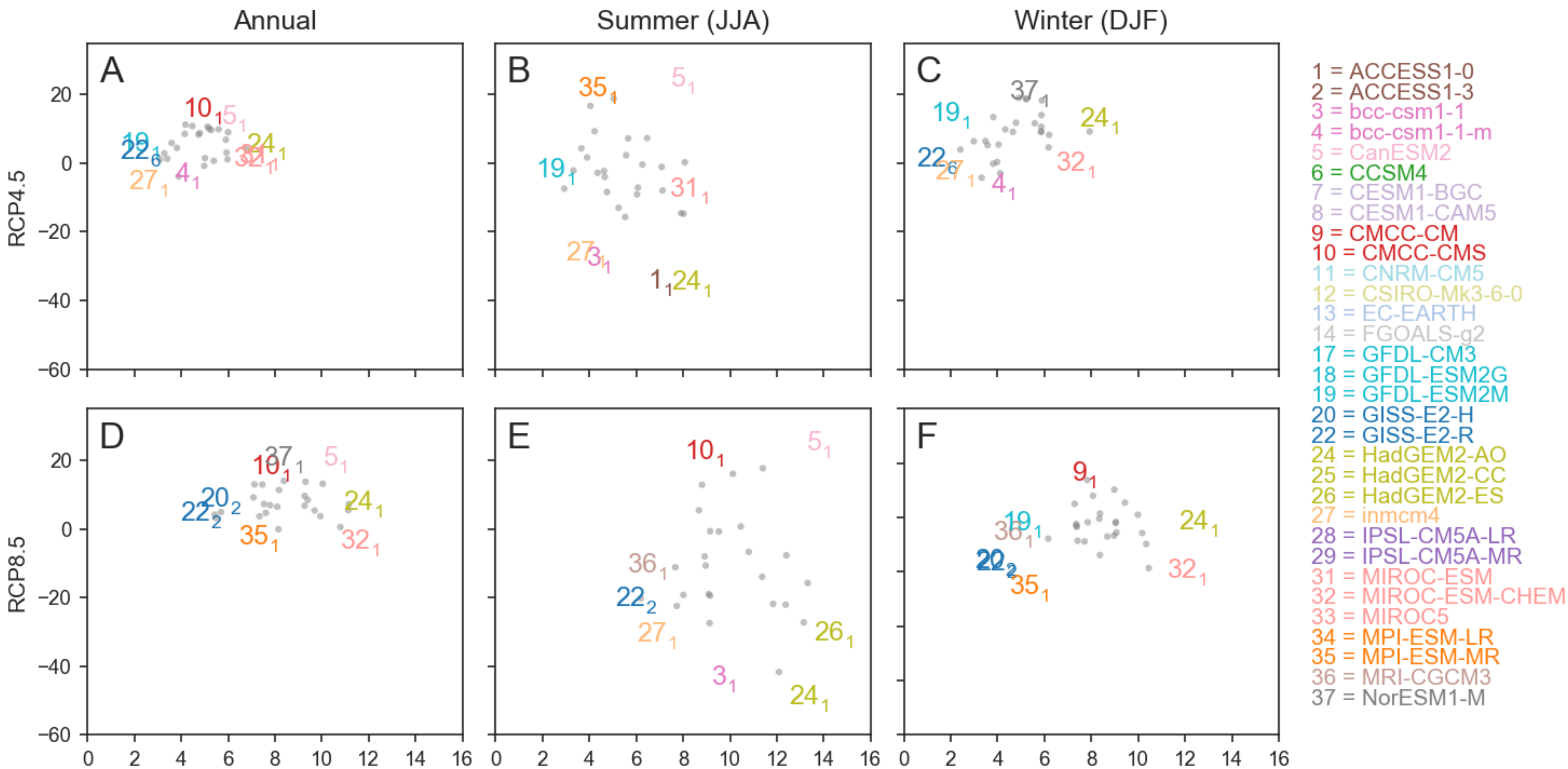

Figure 18. LASSO scatterplots for EPA Region 10, excluding Alaska.

6. CONCLUSION

Locating and identifying useful projections of future climate can be a laborious and technically challenging task. Users must seek to balance using the maximum number of models possible to capture inherent uncertainty in projections of future climate against the practical constraints of the analysis environment. The scatterplot scenario selection process, which uses heuristic approaches such as the *Lasso*, *Four Corners*, *Middle Corners*, and *Double Median* facilitated by the LASSO tool, streamlines the challenging process of selecting a subset of relevant data for decision needs (Bureau of Reclamation, 2015), although it does have tradeoffs. For example, a user might select a too-limited subset of data, unknowingly introducing large uncertainties. Best practices in matching climate information to decision needs and appropriate use of climate information are key to effective use of the LASSO tool.

Setting out to select climate information, users should consider the climate information needed to support decision-making, and employ the approach best suited to the decision context and analytical constraints. The example maps provided within this report provide a readily accessible starting point for those working in EPA Regions across the country.

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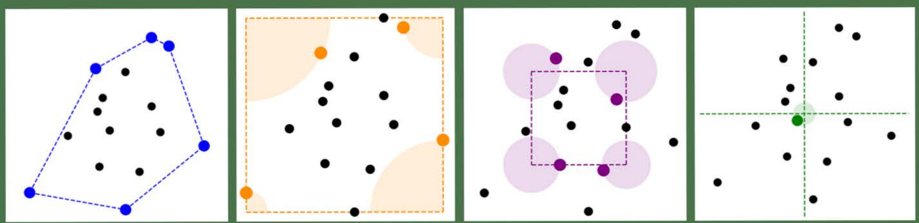

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