Chapter 12
Usability of Climate Model Projections by Practitioners

Ultimately, a goal of climate modeling is to provide useful projections of future climate for policy makers and for "practitioners," those who need to make planning and management decisions based on climate. Practitioners include engineers, water resource managers, and urban planners.

The challenges of communication and use of model projections in planning and management is not trivial. The complexity of models is one barrier: We have used many words to describe the concepts in a coupled climate model. The complexity also comes from the basic difficulty in connecting causes to effects. Causes are emissions and concentrations of greenhouse gases, which first affect the heat input to the climate system (radiative forcing). Effects are climate impacts through the different parts of the system. There is the difficulty and uncertainty in connecting the forcing to a wide range of projected average temperatures and then to an even wider range of regional effects that vary from model to model.[1]

In addition to complexity in cause and effect, there is a more fundamental issue. Climate science relies heavily on simulation models. The use of simulation models often seems strange not just to nonscientists, but even for scientists trained in observational methods who focus more on statistics than on the underlying equations of a system. Therefore, there is a need to communicate the logic of modeling, which requires facing apparent contradictions. For example, one of the major contradictions we have attempted to address is that as models are made more complete, there is little reduction in the *headline uncertainty* (the uncertainty in the global average temperature change).

In this book, we have tried to provide engaged model users with an improved understanding of the logic of modeling, models, and their use in climate science. We have also described model performance and identified essential uncertainties. Even with this knowledge, the use of climate projections in practice remains difficult. There is a growing literature on the use of science-based knowledge, which in the case of climate science is partially motivated by the fact that despite the predictions of dangerous and disruptive climate change, there is relatively little real action. This chapter explores the use of model information, both conceptually and

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[1] Pidgeon, N., & Fischhoff, B. (2011). The role of social and decision sciences in communicating uncertain climate risks. *Nature Climate Change, 1*(1): 35–41.

A. Gettelman and R.B. Rood, *Demystifying Climate Models*,
Earth Systems Data and Models 2, DOI 10.1007/978-3-662-48959-8_12

with case studies. Our goal is to examine the processes involved in the use of model information so that we can help the reader overcome barriers to use of climate model output for improving policy and decision making.

12.1 Knowledge Systems

The literature on the usability of predictive geophysical models (like climate models) relies largely on case studies of the successful use of information. The use of weather forecasts in decision making is so common as to be intuitive. Forecasts of impending extreme weather (within 1–5 days) are used to plan emergency responses. Evacuations are called, or transport (like commercial airplane flights, or train service) is rerouted or cancelled. Other things happen as well, with less media attention. For example, when extreme weather is forecast for winter storms, snowplow drivers are asked to work overtime. When ice storms are predicted, utility crews are brought in from other states to be ready for downed power lines. Still, how to express weather-forecast information, risks and opportunities associated with weather forecasts, and the uptake of that information by decision makers, including individuals, is a subject of controversy and active research.

Perhaps more relevant to the usability of climate information are the studies of seasonal forecasts in decision making. To understand how climate model information is used, it is valuable to understand how “climate knowledge” (e.g., climate projections) relates to other forms of knowledge that are needed to address a particular problem. For example, to manage an ecosystem such as a wetland, climate model information on local precipitation and runoff might be applied as input into a model of the flow of water through the wetland, and the resulting water level. Decisions might need to be made regarding how much water flow is necessary to allow the wetland to function. The water flow may be regulated by an upstream dam, so that the water flow can be adjusted. The climate and derived ecosystem information then informs a portfolio of management possibilities that might be constrained by policy, politics, budgets, and the like. These management needs may include balancing the need to maintain a water level in the wetland, with the needs of water users for agriculture and the need to store water for another season, or to provide for flood control.

The important point is that the climate projection is only a part, and usually an input part, of the decision-making process. The climate information must be relevant to the decision-making process in order to be useful. This has important implications. First are simple things, such as having the right output data from the model (stream flow, or runoff or just precipitation) in the right units. Second are more complex aspects, such as understanding what the uncertainty on the forecast might be and how to reflect that in another application.

A near universal conclusion from the research on usability of information is that it is simply not adequate for climate projections (whether seasonal or longer term) to be placed into a data portal (i.e., made widely available) with the expectation that the projections can be broadly used by practitioners. For the most part, model projections are created by climate modeling groups that produce data, and then leave the data to sit in a metaphorical loading dock or shop window. These data may not ever be accessed. Successful use of climate data in decision making follows from an iterative human process with multiple directions of communication. Models are used by decision makers, and their questions and analysis are used to improve models. This back-and-forth process establishes the relevance of the climate information in the context of the problem.

Simulation output needs to correspond directly to critical inputs. It does not help if a model supplies daily averaged precipitation over a model grid box of ten thousand square miles (100 × 100 miles) if what is needed is hourly stream flow or hourly total runoff for a particular region like a city or a drainage basin, which may span parts of several model grid boxes. The back and forth iteration needs to be between a user (decision maker) and someone who can help interpret the model output (as we describe in the next section). Interpreters need to understand the appropriate and inappropriate use of climate model information. They also need to be experienced users (but need not necessarily build or run climate models themselves).

Putting forecasts into the process of decision making also needs to put the uncertainty associated with the climate projection in the context of the problem. How much of the uncertainty comes from uncertain climate information? The uncertainty discussion is often simplifying, with the realization that the uncertainty of the climate model does not have to be quantified in an absolute sense. This is especially true if the uncertainty associated with climate change is small relative to uncertainties associated with policy, engineered systems, and other attributes of the natural and built environment. As an example, the future impacts of tropical cyclones on a particular stretch of coastline may depend more on what buildings get built on the land than on changes to tropical cyclones impacting the location. An increase in hurricane intensity (wind speed) or frequency may change the expected loss by 50 %. But changing the zoning (what buildings can be built on the land) might result in going from low-density houses to a hotel: If ten $200,000 houses ($2 million) become a $10 million hotel, then because the value increases by a factor of five, the expected loss would increase as well by a factor of five (500 %).

The usability of climate data and knowledge by practitioners is often stated to depend on three things: legitimacy, credibility, and salience.[2] **Legitimacy** describes whether the forecaster is objective, fair, and free of other biases. Is the person making the forecast “legit?” **Credibility** in this context refers to whether the forecast is scientifically valid or credible. Together, legitimacy and credibility suggest the need for decision makers to establish trust in the information they are using: through both trust in the information provider, as well as trust in the model

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[2] Cash, D., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., & Jäger, J. (2000). *Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making*. KSG Working Papers Series RWP02-046, http://ssrn.com/abstract=372280 or http://dx.doi.org/10.2139/ssrn.372280.

used. Most of the discussion in this book so far has concerned the scientific credibility of climate models. **Salience** requires that the information be relevant to a practitioner's problem. More than legitimacy and credibility, this chapter is concerned with salience or relevance, which is difficult to establish.

Relevance or salience often brings forward the need for the evaluation of the data from climate model projections. This is evaluation beyond that performed in modeling centers and through scientific research papers. The characteristics of this evaluation are, often, that it is highly local, is application specific, and uses different variables (derived indices) than provided or evaluated by modeling centers. An example might be taking temperature or maximum temperature and estimating heat waves, or the stream flow in a particular river. The evaluation requires linking past performance with interpretations of the future. Just because a model reproduces the global average temperature or precipitation, that does not mean that the model reproduces the important characteristics of precipitation (frequency and intensity) at a particular location. Further evaluation is often necessary to evaluate models as fit for a particular purpose. This evaluation step in the application of model data is necessary enough that model-data providers should conceive their data as the start of further evaluation rather than just focusing on the practitioner's direct application of the data.

12.2 Interpretation and Translation

The need to make climate model projections relevant to a specific application can be described as the need to translate the information and derived knowledge in the context of a particular problem. The 2012 report from the National Research Council, *A National Strategy for Advancing Climate Modeling*,[3] called for the development of a profession of **climate interpreters**. This recognizes the need to help establish salience. If salience needs to be established for each problem brought forth by practitioners, this represents an enormous task. Therefore, it is reasonable to expect that salience might be obtained in particular sectors or discipline areas of sectors (e.g., agriculture, water management, ecosystems, public health) or for regions with similar geography or climate. In these cases, groups of practitioners may be able to share basic information, for example, how freezing rain will change in the eastern half of North America.

Interpretation of climate model data is part of the necessary iterative process of the use of climate information. It is not simply recasting data and knowledge into a different form. Equally important is for the climate scientist or interpreter to understand the language and context of the decision maker. A simple example is given with the words *anomaly* and *trend*, from statistics, which is often the

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[3] National Research Council. (2012). *A National Strategy for Advancing Climate Modeling*. Washington, DC: National Academies Press.

quantitative language that bridges fields. Words such as *anomaly* and *trend* may take on quite different meanings within the context of a specific field or application. For example, in a general context, an anomaly is something that does not fit (e.g., “the model is anomalous”), whereas in a climate context, the anomalies are usually a reference to a dataset with the average removed. In general, an anomaly in common use is bad, but in a climate timeseries, anomalous events may be a valuable part of the signal, and the word is neutral. *Bias* is another word that has a negative connotation in general usage, but in a climate science context, *bias* is another word for systematic difference from an observation.

More complex questions of interpretation are related to climate parameters that may act in counterintuitive ways, such as the likelihood that in a warming climate there will be more snow in individual storms, yet less snow cover in the late winter and early spring. Explanations and usability of such correlated behavior is not well served by simple metaphors. Likewise, robust and cogent explanations of such concepts are of little use if they are not easily found and included in a practice that connects generation of predictions (or projections) and applications.

Interpretive or translational knowledge exists within an environment that includes multiple paths of communication of knowledge and positions of many stakeholders. So interpretive or translational information is often needed in the application of climate model projections. Individually, this information is not sufficient to ensure usability; however, detailed information about model forecasts or projections is often necessary in the context of a specific problem.

12.2.1 Barriers to the Use of Climate Model Projections

An often-cited barrier to using climate model projections is basic information that describes the model and output products. A climate model needs a manual. The information to be documented includes, for example, glossaries that describe variables and file names, description of specific model configurations and experiment design, and underlying technical documentation of the equations used in a model. This information is used to inform quality, reliability, and trustworthiness (part of “credibility and legitimacy”). There has been significant effort in the climate community to provide this basic information; however, its usability often requires discipline expertise from members of the climate science community. Hence, even at this initial phase of application there is a need for interpretation and translation.

Beyond this basic information, another frequent barrier to the usability of climate data is the fact that the standard data format for climate models is not familiar outside of the climate community. Furthermore, the data format standards for observational datasets differ from those of model datasets. Likewise, standards and conventions of gridded and ungridded datasets differ. An example is the simple difference between gridded data (on a regular horizontal grid) and station locations measuring stream flow along a river. Formats such as those associated with geographic information systems (GIS) are far more common in the practitioner communities. GIS uses a common format for referencing data to a spatial grid on the earth (geospatial), and is used in many planning and engineering fields requiring geo-location (e.g., flood control, city planning). To facilitate exchange, there now exist archives that have "translated" climate model output in common GIS formats. In addition, the practitioner's applications often have far more spatial information than climate models, which can challenge the salience of the climate model data. For example, there are also important differences in how climate models and practitioners' tools represent the quasi-sphericity of the earth.

12.2.2 Downscaled Datasets

A strategy commonly used to address salience is spatial downscaling (see Chap. 8). The spatial resolution of climate models (tens to hundreds of miles or kilometers) is coarse compared to the spatial scale desired by many practitioners, which may be as small as parks within cities, or similar scales to capture the irregular boundaries of watersheds or catchment areas. Many spatial downscaling techniques have emerged, and many practitioners go directly to these processed and downscaled datasets, rather than the original simulations, for their applications. In many cases, these spatially downscaled datasets have also had local bias correction to align the simulated means from the models with historical observations. For example, if the mean temperature of a place is 68 °F (20 °C) and a climate model indicates 70 °F (21 °C), then 2 °F (1 °C) are subtracted from each "simulated" data point both now and in the future. Downscaling can also be done in the time dimension, for example, by turning daily averaged precipitation into hourly precipitation by applying a typical daily cycle of rainfall from observations (*temporal downscaling*). Though these spatial and temporal modifications to the model output provide characteristics that appeal to some practitioners, the impact of modifications on the uncertainty description of model projections is complex. Hence, their contribution to usability of model projections and the influence on science-based credibility is controversial.

Climate model simulations may contain upwards of 100 variables that are used by climate scientists to understand model processes and their evaluation through comparison to observations. The most widely used downscaled datasets usually provide a small set of variables compared with the original model simulation. Most often temperature (mean, daily maximum, and daily minimum) and mean precipitation (daily and monthly) are provided. However, the variables (and time frequency) most salient to practitioners' applications are, often, not immediately available.

Many practitioners are looking for derived values that have well-established sensitivities to weather, usually called an **indicator** or **index**. For example, many applications are sensitive to cumulative measures of warm and cold temperature (heating and cooling degree days, or heat index) and precipitation (frequency and intensity), or lack thereof. Other applications are sensitive to a particular temperature threshold, correlated with, say, a particular time in the growth cycle of a plant or animal. Indices, which often measure persistence and variability, bring attention to modes of variability, for example the Arctic Oscillation or El Niño, and how those modes will change. The diversity of these indices is enormous, and it should be presumed the users of climate projections would need to calculate and evaluate salient indices on their own. Another alternative is to work with interpreters or climate model experts themselves. Just as daily maximum and minimum temperatures can be produced from models, indices can be produced from models. One example might **heating and cooling degree days**. A heating degree day is a measure of each day when the daily average temperature deviates (colder for heating, higher for cooling) from a standard (usually around 65 °F or 18 °C), and represents the cumulative energy demand for keeping buildings in a "comfortable" range. Heating or cooling degree days can be produced while the model is running and saved. But this requires early discussion between those running the model and those using the model, which is hard to achieve.

12.2.3 Climate Assessments

A formal interpretive instrument meant to enhance the usability of climate knowledge, including model projections, is the assessment. The best-known climate assessments are the ones from the Intergovernmental Panel on Climate Change (IPCC).[4] These assessments address the physical science basis of climate change (discussed in Chap. 11), evidence of impacts, and the state of mitigation of emissions and adaptation to present and future climate change. The IPCC makes great effort to define and codify the discussion of uncertainty. There is formal communication in three different working group assessments of (1) climate change science, (2) climate change impacts, and (3) responses for policy makers. Climate models are generally run and evaluated for the first working group (science) and used to estimate (2) impacts and (3) possible policy responses.

Many countries perform assessments themselves to refine usability for a particular region and, increasingly, provide services to improve the usability of climate projections and knowledge. The 2014 National Climate Assessment for the United States[5] puts substantial effort in the development of online information to address some of the issues of provenance and usability discussed earlier. Most other developed countries conduct similar assessments, relying on national climate scientists and policy analysts to interpret the global knowledge and assessment regionally. These assessments rely on the same climate model output, often supplemented with regional climate model output to provide detailed assessments for even parts of countries. Therefore, there is progress in the development of a chain of

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[4] Intergovernmental Panel on Climate Change, http://www.ipcc.ch.

[5] National Climate Assessment, http://nca2014.globalchange.gov.

information, and this is a good source of translation of climate model results into more salient form.

12.2.4 Expert Analysis

Finally, many practitioners look to expert analysis when faced with the complexity (logistical and science-based) and barriers to using climate projections and observations. Practitioners often desire and use fact sheets, narrative and graphical summaries, narrative judgment, guidance, and advice. These products are anchored in climate observations and projections, and the organizations that produce them are effectively "translators" who have substantial expertise in the language and practice of climate science.

An important part of the interpretation of climate projections is the discussion and description of uncertainty. In many successful examples of climate-change planning and management, uncertainty quantification is not necessary. But a salient and qualitative understanding of uncertainty is almost always necessary. Chaps. 9 and 10 have discussed uncertainty extensively in the context of evaluation of climate models for particular uses, and Chap. 11 discussed evaluating confidence in projections. The iterative exchange of information and knowledge among data/knowledge providers and users places the climate uncertainty in context with other sources of uncertainty. Therefore, the scale of the uncertainty, along with an assessment of the state of the knowledge, becomes the essential distillation of climate uncertainty in problem solving.

12.3 Uncertainty

Virtually all discussions of the use of climate data introduce the word *uncertainty* early in the narrative (in this book, see the fourth sentence of Chap. 1). Uncertainty is perhaps the dominant focus. Uncertainty is present in many forms. As we have discussed, uncertainty can be related directly to initial observations (initial condition uncertainty), to the physical climate model (structural uncertainty), and to future emissions (scenario uncertainty). There is also uncertainty from observations used in evaluation (usually a part of structural or model uncertainty).

There is another class of uncertainty about the impacts of the resulting climate projections on the anthroposphere. Impacts of climate change on human systems include impacts on agriculture, built infrastructure, and ecosystems. These impacts are often highly dependent on the local facts and details, including policy and management practices that are in place. There is uncertainty associated with the response of people. The response is often discussed in terms of changes to technology and future energy systems to reduce emissions. This is called *mitigation.* However, on a local scale, there are decisions about land use, policy, management, and engineered systems that strongly affect vulnerability and risk to weather and climate change. This is called *adaptation.*

There is also uncertainty associated with lack of knowledge and uncertainty that comes from different interpretations of knowledge. In problem solving, uncertainty associated with ambiguous definitions of terms often emerges and becomes amplified when the same terms are used in different fields of discipline and practice. This work contains an extensive glossary in an attempt to limit this uncertainty. Many of the terms used in climate modeling and climate science, such as *positive feedback*, have different connotations and meanings in popular usage or other fields.

There is a significant body of work on uncertainty that is driven by climate scientists as well as that associated with experts who study uncertainty as a discipline. In the use of climate projections, it is essential to introduce the entire portfolio of important uncertainties early on in problem solving. By bringing uncertainty to the front of the analysis, the articulation of climate uncertainty in the context of a specific problem is often simplified. For example, if the application is snowpack, then specific uncertainties about temperature thresholds for formation of rain or snow need to be assessed. We will not attempt a comprehensive review of uncertainty, because the dimensions are specific to many problems. The fact that uncertainty changes for each problem is the critical statement. Instead, we focus on the uncertainty usually associated with climate model projections.

Chapter 10 divided uncertainty into initial condition (internal variability) uncertainty, structural (model) uncertainty, and scenario uncertainty. On the timescale of a century, scenario uncertainty dominates (~80 %) on a global scale.[6] Model uncertainty is ~20 %, and internal variability is very small. With the reduction of the spatial scale of interest, on the century timescale, the internal variability is still small (~10 %), but model and scenario uncertainties are comparable in scale. This scale dependence of uncertainty, in which the uncertainty becomes more difficult to define at smaller spatial scales, is a recurring characteristic and is important to establishing salience for use of climate projections.

On shorter timescales, often relevant to planning 20–50 years into the future, the three sources of uncertainty are more equally partitioned between model response and initial conditions. On this timescale, there is not much difference in the model response to different emissions scenarios (the representative concentration pathways, or RCPs, used for climate model projections). Therefore, in many applications, emissions scenarios in the near term do not provide significantly different climates. For spatial scales smaller than global, internal variability dominates uncertainty in the first decade or two. Following those first decades, the model uncertainty and the internal variability are comparable, with scenario uncertainty ultimately assuming a major or dominant position after 50 years.

This partitioning offers information for the practitioner. Notably, the relative importance of uncertainty at different timescales is revealed, which potentially

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[6] Hawkins, E., & Sutton, R. (2009). "The Potential to Narrow Uncertainty in Regional Climate Predictions." *Bulletin of the American Meteorological Society, 90*(8): 1095–1107.

simplifies the range of choices important for a particular problem. Many planning and management activities have small spatial scales and timescales of the next three to five decades; thus, the choice of emissions scenario is less important and the representation of internal variability is more important. Large model uncertainty argues strongly for intensive specific evaluation of model uncertainty (e.g., if the issue is snowpack, is the current temperature correct in the model?) or even the use of multiple models (multiple-model ensembles).

Scenario uncertainty is also associated with the impacts side of the problem. Recall the example of the impact of tropical cyclones on a coastline. That impact will change over time with the built environment, as well as with changes in cyclones. So the scenario for practitioners may also include aspects of the human or natural system impacts that are not treated by the climate model. One difficulty is consistency: If impact scenarios are estimated, like the built environment on a coastline, they should be consistent with the climate scenarios. The human side of the problem may matter between different scenarios, even if the climate projection is similar, as in the case for the example of the built environment around a coastline. Even if cyclones do not significantly change in 30–50 years, the built environment might very well change. The human narrative in scenarios for climate prediction is evolving in 2015, and the current versions of climate scenarios (beyond the RCPs that predict emissions) are called **Shared Socioeconomic Pathways** (SSPs).[7] These scenarios contain not just emissions, but also the growth assumptions used to estimate the emissions, and a narrative describing the assumptions about the future of society.

Initial condition uncertainty is most important when the goal of the simulation is to represent actual "climate forecasts" rather than representative "climate projections." Projections are often conditional: Given a set of emissions, the expected result is a specific climate. But a forecast is more specific. What will happen to the climate in 2020, or 2055 (the latter is more of a projection). The deterministic weather forecast problem is a classic example of a problem that relies strongly on accurate and complete initial conditions. In climate applications, the early decades of a simulation depend strongly of the initialization of the ocean. It is possible for the same model to determine quite different climates from different initializations, which is a motivation for ensemble results. Even if the initializations were (impossibly) perfect, model errors would lead to imperfect forecasts.

There are methods for mathematical quantification of uncertainty. These methods for uncertainty quantification involve understanding how perturbations to the different sources of uncertainty change the results. The computational demands of climate models as well as the complexity make brute-force methods of uncertainty quantification impractical. The uncertainty in a few parameters can be assessed explicitly, by varying different parameters over a range. This is hard to do with

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[7] O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., et al. (2014). "A New Scenario Framework for Climate Change Research: The Concept of Shared Socioeconomic Pathways." *Climatic Change, 122*(3): 387–400.

multiple parameters since all combinations must be tested. However, this is only one dimension of uncertainty (part of **parametric uncertainty**).[8] This point is amplified by the fact that there is no unique way to parameterize a process (see Chap. 4 for discussion); that is, the expert judgments of the model builders differ from model to model, indeed, from model configuration to model configuration.[9] This is another motivation to use ensembles of model projections, which brings attention to the statistical attributes of model performance as a primary measure of uncertainty.

12.3.1 Ensembles

There are three typical types of climate-model ensemble projections. One is an ensemble of different models with the same configuration, each running the same scenario. This is designed to focus on structural uncertainty in the models. Initial condition uncertainty is present, but it goes away for long experiments (over 50 years). It explicitly removes scenario uncertainty. The second type is a set of ensemble simulations with the same model and the same scenario that start with slightly different initial conditions to sample the initial condition or internal variability uncertainty. This explores the possible states in a single model configuration, eliminating structural and scenario uncertainty. The third type of ensemble focuses on scenario uncertainty, for example, by running the same model for more than 50 years to remove model and initial condition uncertainty. All three types are used in climate analysis. Which type is used depends specifically on the application. For example, scenario uncertainty need not be treated on 20- to 50-year time horizons but dominates in the longer term. Using these different techniques leads to the conclusion that on the century scale scenario uncertainty is the largest uncertainty, not model uncertainty.

12.3.2 Uncertainty in Assessment Reports

A leading effort to describe uncertainty in a way that is potentially usable by practitioners is associated with the IPCC assessment reports. Since the year 2000, the IPCC has provided guidance to the writing teams to develop a controlled

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[8] Tebaldi, C., & Knutti, R. (2007). "The Use of the Multi-Model Ensemble in Probabilistic Climate Projections." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365*(1857): 2053–2075.

[9] Schmidt, Gavin A., & Sherwood, S. (2014). "A Practical Philosophy of Complex Climate Modelling." *European Journal for Philosophy of Science* (December 9). doi:10.1007/s13194-014-0102-9.

Table 12.1 Terms and Likelihood Estimates

Term[a]	Likelihood of the outcome
Virtually certain	99–100 % probability
Very likely	90–100 % probability
Likely	66–100 % probability
About as likely as not	33–66 % probability
Unlikely	0–33 % probability
Very unlikely	0–10 % probability
Exceptionally unlikely	0–1 % probability

[a] Additional terms (extremely likely: 95–100 % probability; more likely than not: >50–100 % probability; and extremely unlikely: 0–5 % probability) may also be used when appropriate

vocabulary and to link that vocabulary to quantitative statistical language.[10] One goal was to provide precision to terms such as *almost certain, unlikely,* and *doubtful.* Table 12.1 is from the IPCC supporting material for the 5th assessment report,[11] and it duplicates Table 11.1.

The efforts by IPCC to communicate uncertainty help to define the credibility and legitimacy of the entire body of scientific knowledge.[12] With regard to salience, the IPCC reports are most relevant at global scales and after several decades of greenhouse gas warming: They focus on scenario uncertainty and model uncertainty. These are the more certain projections from models discussed in Chap. 11. The salience or relevance of these reports is frankly inadequate for the needs of practitioners working at spatial scales on the size of watersheds and cities, and/or with planning times of 10–50 years. Further, more detailed analysis working with "interpreters" is necessary in these cases.

12.4 Framing Uncertainty

In practice, uncertainty takes on many different roles in the deliberations of teams tackling climate change problems. In many problems, the first role of uncertainty might be to reinforce political, financial, or belief positions of stakeholders, perhaps serving as a barrier to inclusion of climate change knowledge in the

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[10] Moss, R., & Schneider, S. H. (2000). "Uncertainties—Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC." *World Meteorological Organisation*: 33–51.

[11] Mastrandrea, M. D., Field, C. B., Stocker, T. F., Edenhofer, O., Ebi, K. L., Frame, D., et al. (2010). *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change (IPCC), 2010. Retrieved from http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf

[12] See Yohe, G., & Oppenheimer, M. (2011). "Evaluation, Characterization, and Communication of Uncertainty by the Intergovernmental Panel on Climate Change—An Introductory Essay." *Climatic Change, 108*(4): 629–639.

problem-solving environment. A common-heard refrain is, "If impacts are uncertain, then nothing should be done."

Generically, this use of uncertainty to position stakeholders needs to be understood by climate scientists and climate-science interpreters. The argument is often made that the reduction of uncertainty is needed to overcome barriers to action. However, there is little evidence that reducing uncertainty yields better policy outcomes or decisions.[13] Climate science and climate modeling is a science of increasing complexity, and reduction of uncertainty in a quantitative sense is unlikely. The reduction in uncertainty comes from adding more complexity and gaining more certainty about the answer, but not necessarily by reducing quantitative uncertainty: It is increasing confidence in the answer and confidence in the number of different types of uncertainty that can be addressed. Furthermore, given the role of uncertainty to bolster stakeholder positions, uncertainty can always be used to breed doubt. Therefore, it is a fallacy to maintain that reduction of uncertainty is the key to improving usability of climate projections.

Fortunately, the successful use of climate projections in planning often does not require the strict quantification of uncertainty. Practically, complex specifications of uncertainty add another level of expertise that must be interpreted, and the incremental changes to already highly uncertain parameters are not of sufficient value to justify the cost of the additional expertise. Complex specifications may make it harder to interpret climate projections by a broad community of users.[14]

Though some practitioners desire quantitative measures of uncertainty, for many people "uncertainty narratives" are all that is required to justify incorporation of climate change into planning and management. Uncertainty narratives can be framed in different ways for different problems. One productive way is to frame the uncertainty in the context of known vulnerabilities to weather. If there is an already-observed climate trend of important weather events (for example, extreme precipitation), and if that trend is consistent with model projections, then uncertainty can be discussed in relation to known weather vulnerabilities. This brings attention to the climate model's ability to represent weather features. For example, if a climate model does not represent the spatial and temporal organization of severe thunderstorms generating large amounts of rain in the central United States during summer, then it is difficult to substantiate uncertainty descriptions in regard to changes in this phenomenon. In the case of severe thunderstorms, most climate models are missing a key process (hail formation) at a subgrid scale they cannot represent.

It is also true, in many applications, that the availability of water is dominated more by policy and built infrastructure than by precipitation: "water flows uphill towards money"[15]. The spatial scale important to the water supply of a megacity is

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[13] Lemos, M. C., & Rood, R. B. (2010). "Climate Projections and Their Impact on Policy and Practice." *Wiley Interdisciplinary Reviews: Climate Change, 1*(5): 670–682.

[14] Tang, S., & Dessai, S. (2012). "Usable Science? The UK Climate Projections 2009 and Decision Support for Adaptation Planning." *Weather, Climate, and Society, 4*(4): 300–313.

[15] Reisner, M. (1993). *Cadillac Desert: The American West and Its Disappearing Water*. New York: Penguin.

likely to include watersheds of much greater spatial scale than the city and likely to be very far removed from the city. Climate uncertainty is one piece of information input to the policy process to help determine the built infrastructure. Other inputs would include population changes and the economics of building and maintaining the infrastructure: reservoirs, aqueducts, and pumping stations. The projections from climate models might be of sufficient certainty to motivate policy changes, such as managing seasonal runoff from high mountains in order to benefit human and natural systems. The long lead times to form, approve, permit, and implement a water system allow for both the accumulation of additional observational evidence as well as the improvement of models—to inform actual specification of evolving infrastructure.

Each problem has its own unique requirements on uncertainty, and these requirements can simplify the inherent complexity of the uncertainty sources. At least the analysis can reveal the key uncertainties. For example, a problem to be addressed in the next two decades, with a solution needed to function for the two decades after implementation (i.e., a lifetime in the next 40 years), has relatively little sensitivity to the carbon dioxide emission scenario. A problem requiring specific knowledge of Arctic sea ice in the next 20 years relies on model components that have strong sensitivity to the initial state (ocean currents), a rapidly changing physical environment (melting ice changes radiative forcing), and complex multi-scale physics that are not especially well represented (see discussion in Chap. 11, and Fig. 11.6).

The more specific the application, the easier it might be to characterize the key uncertainties. If the application is to estimate sea ice to determine the feasibility of shipping routes in certain seasons in the Arctic, then the key features are narrowed to a season, and perhaps a particular threshold (sea-ice thickness less than some threshold for which an icebreaker is available). This might lead to specific uncertain processes that govern sea ice in particular seasons. Instead of looking at all available model simulations with large uncertainty (see Fig. 11.6), a subset of models could be used. The subset of models would contain those models with a good current sea-ice thickness in a particular season.

Therefore, a productive way is to step back and focus on the state of the knowledge in Fig. 11.1. This ultimately relies on fundamentals of the scientific method—observations, theory, simulation; the emergence of consistency among these three pillars; and reproducibility by many investigators coming from different approaches and scientific techniques. The state of knowledge is different for different processes and phenomena.

It is well established, for example, that sea level will rise as the planet warms up. Our knowledge of the amount of sea-level rise remains incomplete (see Chap. 11). One way to narrow the range of knowledge is to consider how fast ice might melt and increase sea level. Estimates of the physical timescale can be combined with timescales of planning, building, operations, and maintenance to narrow the range of the incomplete knowledge. In this scenario, competing explanations are of little consequence to practitioners. Placing the problem in context allows evaluation of the sources of uncertainty and whether or not there is adequate information for defensible decision making.

12.5 Summary

The key to using climate model output is understanding the credibility of the model, the legitimacy of the model, and the salience or relevance of the projection. Credibility comes from the type of model and the model development process. Legitimacy comes from a detailed understanding of uncertainty in all its dimensions for a particular problem. Salience (relevance) comes from understanding of a particular problem. Climate model output must be made relevant, and having translators or interpreters familiar with a particular application has been effective in many cases.

Climate information in many cases is just one dimension of a problem, and it may not be the dominant dimension of uncertainty, particularly where the human sphere is involved. It may matter more how society changes than how climate changes to determine the load on a particular resource (e.g., water, land). So climate model output must be put into perspective, and uncertainty assessed against particular problems to determine salience.

The use of interpreters and a focus on salience allows the dimensions of uncertainty to be reduced. These dimensions are different for particular problems. The prediction problem determines the timescale, and that determines the balance of scenario, initial condition, and model uncertainty. It may also help determine how to construct an ensemble of models for a particular problem. And the particular impacts determine what portions of model uncertainty are most important. Examples of particular aspects of model performance include intense summer convective precipitation over a region, or a particular mode of climate variability like tropical cyclones, the Asian monsoon, or blocking events. Focusing on a particular process allows a better assessment of uncertainty in a particular model, or an ensemble of models. This can be done with specific observations. It also helps to fit the model output into a particular problem, and getting the particular data on the right spatial and time scales.

We hope that this approach is useful in helping to frame the problem of assessment and use of climate models from broad uncertainties to specific and more tractable uncertainties. These uncertainties can be qualitative or, when narrowed sufficiently, even made quantitative.

For most problems, if framed in this way, it is not necessary to wait to use a future model with reduced uncertainty, and the “best” model or set of models may be different for different processes. Climate models provide a wealth of salient information that is ready to be interpreted and assessed to make specific projections.

Key Points

- Climate uncertainty may be a small part of decision making.
- Perfect models and perfect projections are not necessary for applications. Uncertain projections have value.
- Critical uncertainties may be different for each application of climate model information.
- Focusing on the particular application is one way to better understand uncertainty in climate models.