UNSW Institute for Climate Risk & Response

climate extremes ARC centre of excellence

Working with Uncertainty in Climate Planning and Adaptation

Key Messages

1

Uncertainty arises from future human behaviour and the complexity of the climate system.

2

Climate models are powerful tools to help us understand how our decisions might affect the climate system.

3

Planning and adaptation responses require an understanding of the assumptions and uncertainty in climate projections.

The future is uncertain. We do not know the precise nature of future change - when, where and how it will unfold. Yet, we are used to making decisions in the face of uncertainty, even when the stakes are high. We face life changing medical decisions with incomplete information, invest in the stock market without knowing future price trajectories, or plan large events with uncertain weather forecasts. Our level of certainty guides decision making and guards against inappropriate actions and impacts.

Ideally, we want information which clearly shows whether one kind of outcome is more likely than another. This can be extremely valuable, even when information is incomplete, as it can change our understanding of the relative likelihood of different outcomes.

Whether we're aware of it or not, we all often use mathematical or computational models to provide this kind of information. They express experts' understanding of relevant, complex phenomena in equations that can quickly give useful indications of likely outcomes. They are the basis of the systems which we encounter on a daily basis, for example, aircraft control systems, safety technology in cars, GPS navigation, or calculating medical dosages.

Understanding uncertainty helps us make more informed decisions.

In the context of adapting to a changing climate, climate models offer us information about possible future outcomes. Climate models can provide guidance on the implications of our decisions for the earth's future climate, but they cannot tell us exactly what to do. So, what is the nature of the information climate models provide, and how should we use this information?

Climate models

Climate models are highly detailed, quantitative computer-based representations of the Earth's climate which incorporate our knowledge of the physical world, including physics, chemistry and biology. They simulate an immensely complicated system, representing the atmospheric and ocean circulation, light and heat transfer, ocean density and salinity, clouds, soil moisture, photosynthesis, carbon and nutrient cycles and much more. Given this complexity, their ability to reliably reproduce and predict realistic phenomena, such as storms, fronts, heatwaves and droughts from relatively simple physical principles is truly remarkable. They are extremely valuable and useful tools.

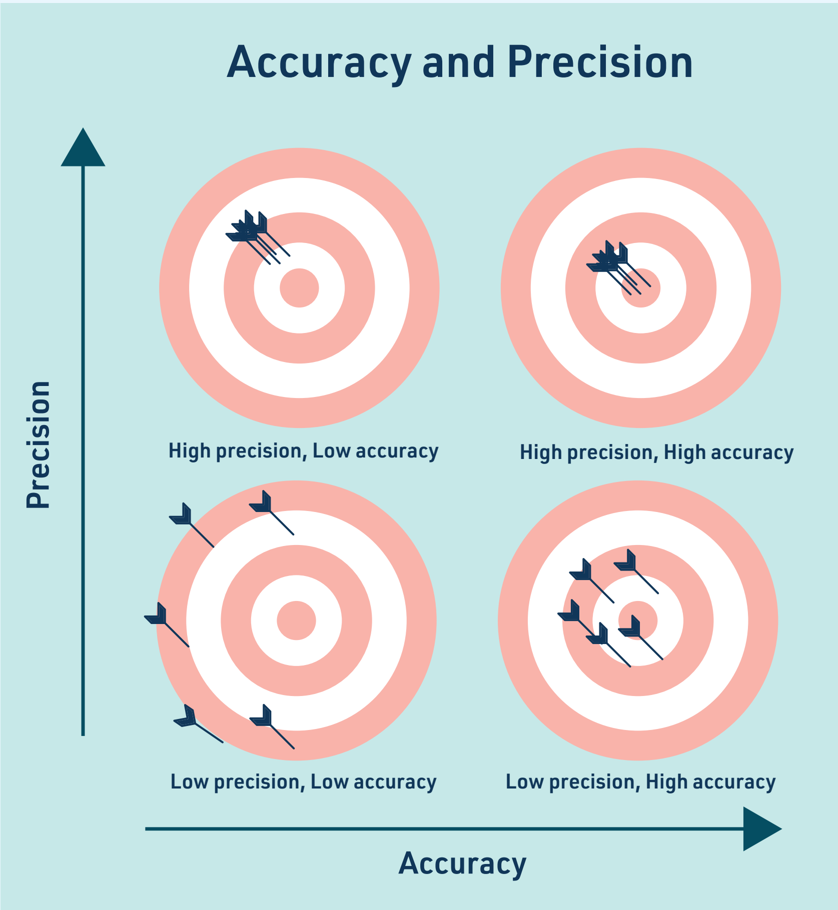
Uncertainty in decision making. Source: https://adaptalaska.org/explore-changes/uncertainty-climate-projections/

Future projections made with climate models produce outcomes in many hundreds of physical variables to ten or more decimal places for the next 100 years or so. This precision (see Explainer Box: Precision v Accuracy) however, is easily misinterpreted, often resulting in climate model data being used in inappropriate ways. The simulations provided by climate models should be thought of as a representation of the consequences of decisions we might choose to make (see The ARC Centre of Excellence for Climate Extremes | Climate modelling – a closer look).

Climate model simulations are not predictions of our future. They are projections of the impact of decisions we might make on future climate, with varying degrees of uncertainty. One way of thinking about climate model simulations is that they provide plausible futures.

Precision v Accuracy

Accurate estimates are centred on the correct value. Precise estimates are similar to each other. Either, neither, or both can apply to an estimate. So top left is a very precise estimate, but not a very accurate one. Bottom left lacks precision or accuracy. Top right is ideal - both an accurate and precise estimate.



To understand why climate model data contain uncertainty, and how we might work with this uncertainty, we need to examine:

1. The assumptions made in a future climate simulation
2. How variability in the climate system is described and represented in models
3. Why even the most complex climate models are only approximations of the real world
4. How computing power constrains our ability to resolve aspects of uncertainty
5. How we work around computational constraints to get information about relevant, local, future impacts.

1. Assumptions for simulations

To run each future climate simulation, we need to make critical assumptions about future human behaviour, such as:

the nature of economic and technological development,

the types of energy and agricultural systems we'll use in the future,

or incentives to drive change such as carbon pricing.

In particular, we need to know what these assumptions will mean for future greenhouse gas emissions over the period of simulation. This is the largest source of uncertainty in estimating future climate. Future simulations represent the projection of a collection of assumptions about future human behaviour onto future climate. These assumptions are typically explored by describing emissions scenarios such as Representative Concentration Pathways (RCPs) or Shared Socioeconomic Pathways (SSPs). Depending on the emission scenario, model results can give a wide range of possible outcomes.

2. Describing climate processes: Variability

The climate system is highly variable, meaning that aspects of the weather, such as temperature and rain, change naturally from month to month, season to season and year to year. In a climate model, we include our understanding about variability in the climate system by considering two different categories of variability.

- First, internal variability in the climate occurs without any change to external factors such as solar radiation changes, greenhouse gas emissions and volcanic activity. This is the part of variability that is not predictable, can be present on timescales from seconds to decades, and embodies the chaotic aspects of the weather and climate system. Individual weather events fit in this category.
- Second, forced change represents variability that is driven by external factors including solar radiation changes, greenhouse gas emissions and volcanic activity. The relative frequency of particular kinds of weather events is affected by forced change.

This is called internal variability versus forced change. Researchers can create a collection of simulations that allow this distinction to be assessed, called an internal variability ensemble, or an initial conditions ensemble. The nature of internal variability can change as external forcing changes the climate system, making it particularly hard to quantify - it's an active area of research within the climate community.

3. Describing climate processes: Representation in models

There are differences in the way researchers represent processes within climate models (Figure 1) when developing their models. This can stem from the focus of the study (e.g. the area of study relates to aerosols in the atmosphere), how spatial resolution approximations are implemented (e.g. small or large scale investigations) or which processes are included and excluded in their model (e.g. whether or not nutrients play a role in plant growth). Model development can be driven by differing national priorities and vary amongst different research institutions around the world. The differences are embodied in different models in multi-model ensembles, for example the Coupled Model Intercomparison Project (CMIP) ensembles - an international project to support national and international assessments of climate change.

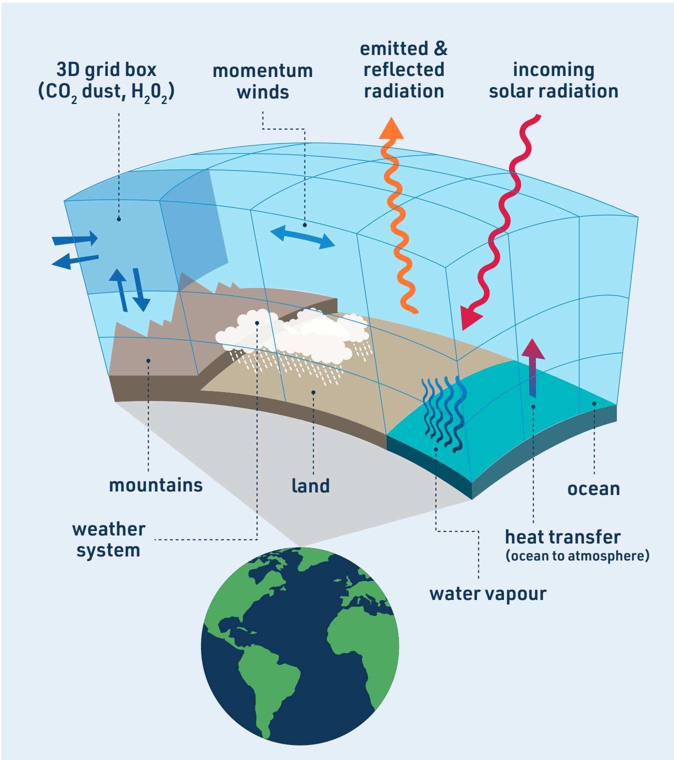


Figure 1: Illustration of the three-dimensional grid of a climate model. This is a simplification, many more processes are included in the atmosphere, ocean and land. Image: Adapted from Earth's Climate: Past and Future by William F. Ruddiman.

Therefore, despite the precise nature of each model simulation, there are many reasons why models may differ from each other, even when all models are exposed to the same change in atmospheric concentrations of greenhouse gases (via, for example, an emissions scenario). Ultimately the differences between models results in a wide range of possible outcomes for a particular emissions scenario.

4. Limits of technology: computing power

Even if the future emissions assumptions were correct and we had a 'perfect' model, there are limitations in the fidelity of our representation of the climate system. This is partly to do with complexity of climate models and the limits to computing power. Models can take months to produce a single simulation on a large supercomputer costing many millions of dollars, processing millions of lines of code millions of times on thousands of processors. Even then they typically only give us useful information at spatial scales of 100s of kilometres.

The limitation in computing power and time means that some of the fundamental equations about how our climate behaves, transfers heat, its chemical composition and radiation need to be approximated. This is because some key climate processes operate at a very small scale, such as intense local rain events, which are unable to be described by models that process data at spatial scales of hundreds of kilometres. While newer computers and advances in models gradually improve the situation, this limitation will always be part of simulating a very complex system.

5. Uncertainty at local scales

The outputs of climate models come in the form of values of a wide range of variables, including temperature and precipitation, in a three-dimensional grid that covers the land, atmosphere and oceans. These values may be archived as hourly, daily, monthly, or annual averages throughout the simulated time-period but are calculated roughly every 20 minutes of the simulation period. Because of the computational limitations we discussed above, the spatial size of each cell in this grid, called the model resolution, can be more than 100km, meaning we might only have a single value of precipitation and temperature for each 100 km x 100 km.

If we are planning local infrastructure, protecting an ecosystem or pricing an insurance policy, we need to know as much detail as possible about local impacts, at much finer scales than those produced by climate models. This is where "downscaling" is useful.

Downscaling (see The ARC Centre of Excellence for Climate Extremes | Climate modelling - an overview - The ARC Centre of Excellence for Climate Extremes) involves using a regional climate model (or a statistical or machine learning model) to simulate a specific region of interest at higher resolution than a climate model, using climate model data to inform the simulation.

Downscaled climate projection data forms the basis of most Australian state-based future climate planning (e.g. the New South Wales and Australian Regional Climate Modelling project (NARCLiM)), and is used to drive climate impacts' models for different sectors. Downscaling introduces additional uncertainty into projection information - there are many equally plausible ways to downscale that deliver different (and sometimes contradictory) outcomes.

Working with the information we have

Translating projection information and uncertainty from emissions scenarios through to local impacts is very computationally demanding. Unfortunately this means we cannot afford to propagate all possibilities for an area of interest. Only around 20% of climate models can be downscaled to a regional level before existing computational resources are exhausted. Practically this means we can also only afford to downscale a small fraction of the initial conditions ensemble members for each model. This subset of model simulations must be chosen carefully to balance a range of impacts-related interests and use-cases. These might include agricultural drought impacts, flooding, storm damage and ecological impacts. It is important to note that we are unlikely to be able to tell how much, or which parts of the full spectrum of possibilities this subset occupies for a particular application.

Gadi, a high-powered supercomputer at the National Computational Infrastructure (NCI) based at the Australian National University. Source: https://science.anu.edu.au/research/facilities/national-computational-infrastructure

So while we have a range of possible outcomes for most impact assessments, we know that it's not the full range of possible outcomes - these are known unknowns. We also can't discount the possibility that there are other different possible ways to build climate models that are not yet part of the range of projections in CMIP type ensembles, or that the sampling of internal variability in initial conditions ensembles isn't perfect - these are unknown unknowns.

Understanding these sources of uncertainty, and their incomplete representation shows us why the precision of climate model data can be easily misused. For example, if we are interpreting future rainfall to 10 decimal places using a single simulation as a future prediction, it is almost certainly going to be wrong. This single simulation will represent a very particular set of assumptions and choices, and while it may well be as likely to be correct as any other simulation, it is only by considering the complete collection of simulations that span the suite of assumptions we are required to make that we can begin to understand which outcomes are more or less likely. Just as rolling dice hundreds of times might be required to understand whether they're loaded, we need many climate model simulations to gauge which outcomes are most likely.

How should we use information from climate models?

Using climate model information effectively requires developing a qualitative understanding of how the kinds of changes that are projected by climate models would affect your particular interests. Here are a couple of suggested approaches as a guide:

1. Storylines

Use different emissions scenarios to understand broad scale differences in outcomes as a result of different emissions pathways. Use the available model spread (see https://climateextremes.org.au/a-closer-look-at-climate-modelling/) as a rough guide to how concrete those differences are likely to be. A simplified version of this is called a 'storyline' approach. For example, your region of interest may be projected to have a slight drying on average with increased heat, or significant rainfall increases overall with increased rainfall variability. These two plausible futures or 'storylines' might bracket the range of outcomes, and your preparedness could simply result from working through what these two cases might mean for your risk, in terms of pricing, supply chains or clientele.

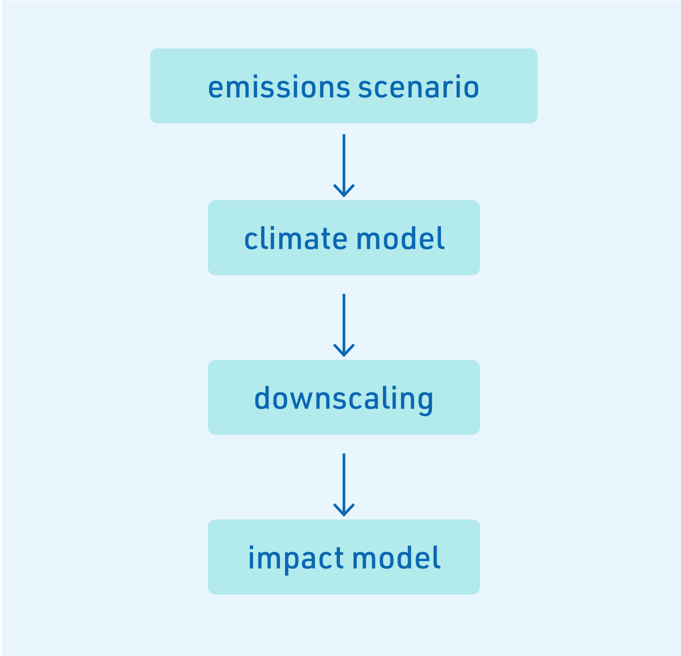
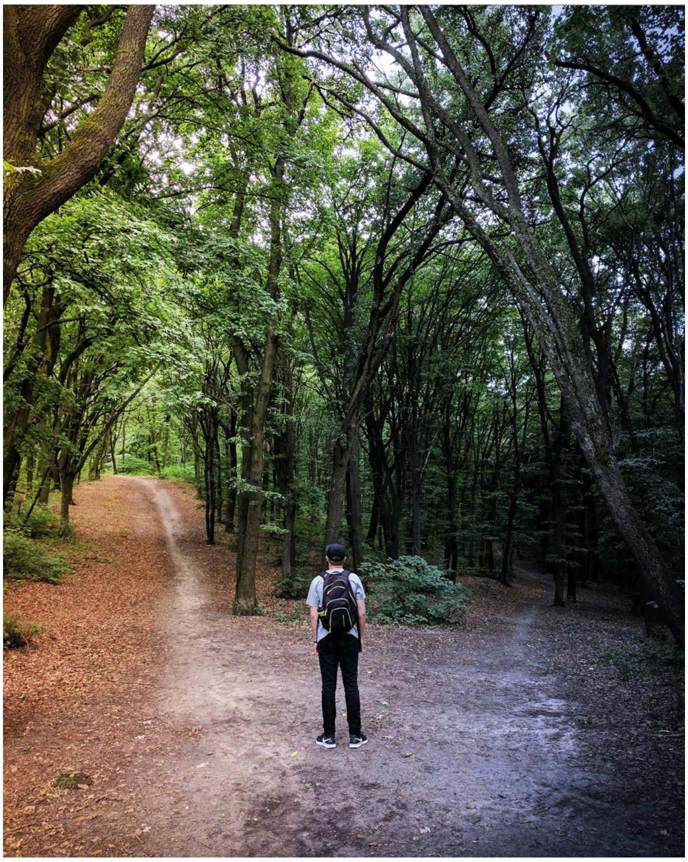


Figure 2: Simplified pipeline of information

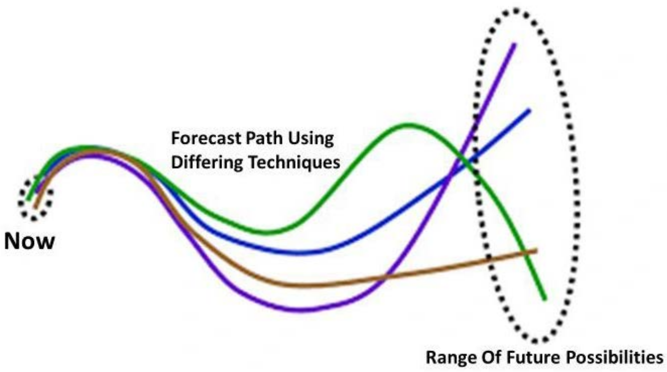
The distribution of possible outcomes that exists in each step of our pipeline of information (Figure 2) is unlikely to cover all of the possible outcomes. It only covers a range of possibilities, and we know this range does not represent a true distribution of all the possible outcomes.



2. Estimate probability

Alternatively, you could choose to use or develop tools like downscaling, bias correction, machine learning, ensemble and model skill selection, weighting, averaging or independence assessment, and develop something closer to a real probability estimate. For a specific application, it's quite likely that only some models provide useful information - different climate models are good at different things - so using all of them might be a bad idea. At the same time, using too few will artificially narrow the uncertainty bounds that we have, especially if the subset of models chosen are quite similar. Be aware that this process will incur considerable time and cost penalties and require a high level of expertise. Nevertheless, an approach that customises information for your interests can result in much more nuanced and useful information.

Although you can try to account for some level of uncertainty, some will always remain. In both (1) and (2) above, uncertainties and model agreement can map onto different climate variables in very different ways. For instance, temperature changes are relatively clear, despite all these unknowns (so we may well be able to make concrete decisions where they rely on knowledge of temperature change). Precipitation, especially at local scales in Australia, is generally not (so you may simply need to be resilient to a wide range of possibilities).



The future has multiple possibilities. Source: https://www.linkedin.com/posts/neetu-khandelwal-11636623b_even-if-multiple-people-start-off-with-exact-activity-7151759707655884801-_kNd/

Also keep in mind that the direct effects of changing climate are only part of the likely impact on your area of interest. An assessment of vulnerabilities and the relative risks and impacts of things like supply chain disruption, availability of key services or market changes is a good place to start, individually or in combination with each other. From there, a hierarchy of externalities that could affect your interests could be useful - for example a halving of agricultural output would not simply represent an impact on the agricultural sector.

And finally...be upfront with your assumptions.

Finally, we want to reinforce that every time you see future climate information, all of the points and caveats discussed above will apply. The information you see will be based on many different assumptions. It is important to be aware of what these might be and be critical of the information you are given so you can obtain appropriate data for your application. If you are a producer or consumer of climate information, it is important to recognise these uncertainties so that you can assess information with confidence.

Conclusion

Climate models are powerful tools that form the basis of our understanding of how future climate will change, and are critical for informing adaptation and some mitigation decisions. Even as they evolve with our understanding of the climate, their projections are and will always be fundamentally conditional upon our future behaviour, and only ever be partial representations of the complete climate system.

But a greater understanding of how climate models work, their limitations and assumptions will allow more effective utilisation of the information they produce. Acknowledging uncertainty as a fundamental part of future climate change is a key step for decision makers to minimise risk by appropriately using the wealth of information climate models already provide.

Written by

Gab Abramowitz

is a Chief Investigator in the ARC Centre of Excellence for Climate Extremes. His research interests include uncertainty quantification, understanding how models of natural systems are used for scientific inference and a range of machine learning applications in climate science.

Ben Newell

is the Director of the UNSW Institute for Climate Risk & Response. He leads the interdisciplinary institute which addresses climate risk, emphasising effective communication, behaviour change, and collaborative partnerships with industry and government. He specialises in the psychology of decision-making, applying behavioural insights to address societal challenges, particularly climate change.

Angela Kaplish

is Lead Knowledge Broker at the ARC Centre of Excellence for Climate Extremes. Her work centres around translating and explaining climate science for government audiences. She is particularly interested in providing and disseminating climate science for policy making.

Andy Pitman

is the Director of the ARC Centre of Excellence for Climate Extremes. His expertise focuses on terrestrial processes in climate modelling, including the water, carbon and energy fluxes, extremes and the robustness of climate models at various scales.

Produced by

Engagement and Impact Team - Knowledge brokers: Angela Kaplish, Alice Wilson
Communications: Laure Poncet **Graphic design:** Georgina Harmer

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Contact
clex@unsw.edu.au

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