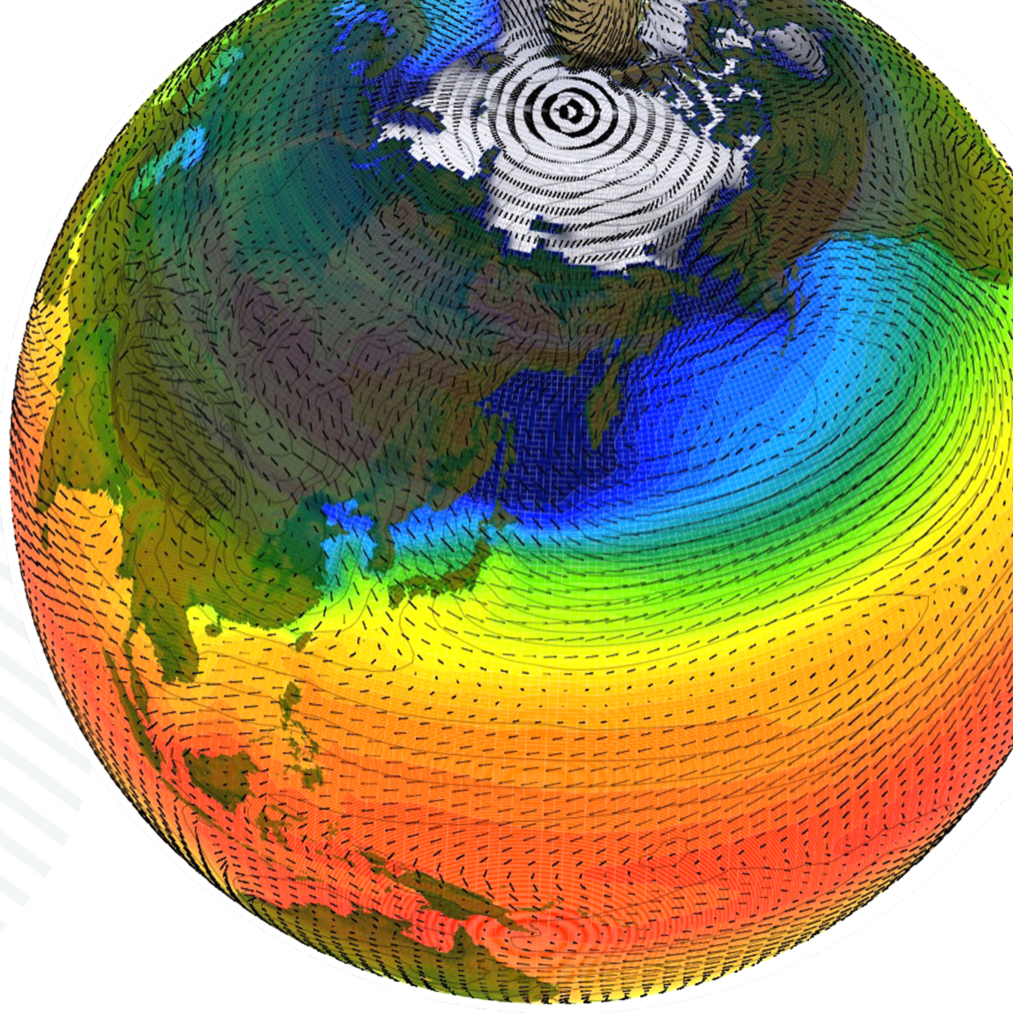

December 2024

CMIP6 Frequently Asked Questions:
A resource for water managers

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Introduction

The WUCA CMIP6 Working Group asked the authors to develop a CMIP6 Frequently Asked Questions (FAQ) document for water managers which would assume little or no previous experience with CMIP6 and other climate-model datasets. The goal was to develop a dozen or so highly relevant questions — and clear responses — to aid in the use and interpretation of CMIP6 datasets, with a focus on the contiguous United States (CONUS). The FAQ questions were initially proposed by Working Group members, and then iteratively refined in collaboration with the Working Group, resulting in 13 questions. The document benefited considerably from reviews by the CMIP6 Working Group and by external subject matter experts.

Each question has a “short answer” (1–2 paragraphs) and a “long answer” (2–5 pages), including figures where appropriate, recommendations for further reading, and other references. A glossary and reference list are also available at the end of the document.

Frequently Asked Questions

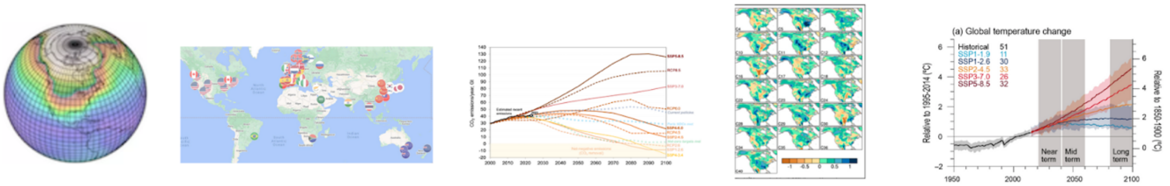
Q1. What is CMIP6?

Short answer

CMIP6 (Coupled[1] Model Intercomparison Project, Phase 6) is the most recent organized international "roundup" of global climate projections from several dozen climate models. The models are run using standardized input scenarios (e.g., of greenhouse gas emissions and other climate drivers) to produce thousands of simulations of past and future climate conditions that get widely used in climate research, assessment, and adaptation planning.

Long answer

Several dozen comprehensive climate models — global climate models (GCMs) and more complex Earth system models (ESMs) — have been developed by modeling centers around the world. Every six to eight years, the Coupled Model Intercomparison Project (CMIP) systematically captures how climate change is depicted by the current generation of climate models, by coordinating the various groups to run their models under common sets of prescribed inputs and conditions. This ensures that any differences in the model output are due to differences in how each model simulates the climate, not discrepancies in the input assumptions. CMIP is carried out under the auspices of the World Climate Research Program (WCRP) of the World Meteorological Organization (WMO), but the funding for the modeling centers and the CMIP runs themselves come from the respective national science agencies.



59 global climate models

From 30 modeling centers worldwide

Using up to 8 emissions scenarios

Run at least once, up to 99 times per model

Generating a total of 2500 projections of future climate

Figure 1.1. Schematic of the setup for CMIP6, with key statistics. (Referring specifically to the ScenarioMIP activity in CMIP6; see below.)

The first phase of CMIP was carried out in the mid-1990s to provide coordinated model simulations for the Second Assessment Report (1995) of the Intergovernmental Panel on Climate Change (IPCC). Subsequent CMIPs have also been scheduled to support the IPCC

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[1] "Coupled" refers to the linkage of atmospheric and ocean processes within a climate model – a structure that was more novel at the time of the first CMIP 30 years ago but has since become standard.

reports, and the CMIP model simulations have become integral to the IPCC assessment process — and to national, regional, and state-level climate assessments[2]. CMIP5 supported the IPCC Fifth Assessment Report (AR5) and later the Fourth National Climate Assessment (NCA4; USGCRP 2017, 2018). The most recent phase, CMIP6 (Eyring et al. 2016), supported the IPCC Sixth Assessment Report (AR6; IPCC 2021) and the Fifth U.S. National Climate Assessment (NCA5; USGCRP 2023a).

Many models in CMIP are variants of the same parent model; the 59 models in CMIP6 represent about 27 model "families" depending on how they are counted (Brunner et al. 2020). Also, collaboration among modeling centers means that different models often share large blocks of code that represent certain key components of the Earth system, e.g., ice-sheet dynamics. Consequently, the true diversity of the models in the CMIP ensembles is less than a simple count would suggest.

There are few formal criteria for a modeling center and its model(s) to participate in CMIP, beyond the capability to use the CMIP-prescribed inputs and then output the model results in standardized data formats. Accordingly, the CMIP models have been referred to as an "ensemble of opportunity" (Tebaldi and Knutti 2007). While modeling centers would be unlikely to put forward a model that was especially poor, evaluations have shown there is a wide range in model performance (i.e., the model's fidelity in reproducing historical climate patterns for some variables; see Q2), depending on the metric. Most CMIP6 models are updated versions of models that participated in CMIP5.

Global climate models were initially designed to study how the climate system works, including its large-scale response to drivers such as greenhouse gases (e.g., globally averaged temperature change, changes in global precipitation patterns). Being designed and run originally for understanding the science of climate has led to tradeoffs that can limit the models' suitability for regional climate applications. The modeling community is grappling with the question of how future CMIPs can continue to advance the frontier of climate modeling and science while also effectively delivering climate projections as a service to support adaptation planning (e.g., Jakob et al. 2023, Baldissera Pacchetti et al. 2024, Stevens 2024).

As with previous CMIPs, CMIP6 comprises many different modeling *activities* and *experiments,* each with its own objectives. The activity in CMIP6 that is most relevant to assessment and adaptation (e.g., in water management), is called *ScenarioMIP*. Outside of climate-modeling circles, to say "CMIP6 projections" typically means "the projections that were output by the ScenarioMIP modeling activity" — and not the other 20 activities in CMIP6. This FAQ follows that common usage.

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[2] "CMIP4" was skipped to align the numbering of the CMIPs and the IPCC Assessment Reports.

	CMIP3	**CMIP5**	**CMIP6**
Initial GCM data availability	2006	2012	2019
Main emissions scenarios	*SRES scenarios:* B1, B2, A1B, A1FI, A2	RCP2.6, RCP4.5, RCP6.0, RCP8.5	SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, SSP5-3.4-OS, SSP5-8.5
Historical climate period	1880–2000	1850–2005	1850–2014
Projection period	2001–2100	2006–2100+	2015–2100+
Participating modeling centers	16	30	30
Participating models	25	55	60
Total model runs (i.e., projections)	120	250	2500
Horizontal resolution in atmosphere (i.e., gridcell size)	100–500 km (median: 250 km)	50–300 km (median: 170 km)	50–250 km (median: 130 km)
Timestep of archived data	Monthly	Daily and monthly	Sub-daily, daily, and monthly
Selected climate assessments that used these projections	IPCC *AR4*	IPCC *AR5; National Climate Assessment* (*NCA3*, *NCA4*)	IPCC *AR6*; *NCA5*

Table 1.1. Comparison of the characteristics of the last three Coupled Model Intercomparison Projects (CMIP3, CMIP5, and CMIP6) and their participating climate models. (Updated from Table 11.2 in Lukas et al. 2020)

Further reading:

- Hausfather (2019). *Carbon Brief* Explainer: CMIP6: the next generation of climate models explained.
- McSweeney and Hausfather (2018). *Carbon Brief* Q&A: How do climate models work?
- Eyring et al. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. (more technical)
- O'Neill et al. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. (more technical)

Q2. How is CMIP6 different from CMIP5, and is CMIP6 better?

Short answer

CMIP6 differs from CMIP5 in several ways, although these differences do not set CMIP6 completely apart from its predecessors. CMIP6 models generally have higher spatial resolution and greater complexity than their CMIP5 counterparts, although the range in those attributes across the CMIP6 ensemble overlaps with the CMIP5 range (e.g., Figure 2.1). For measures of model performance, general improvements are seen in CMIP6, again with substantial overlap between the CMIP6 and CMIP5 ensembles (e.g., Figure 2.2). CMIP6 does include projections under a greater diversity of emissions scenarios than CMIP5 (8 vs. 4) and includes many more model runs per model/scenario pairing, on average.

As climate modeling continues to develop and mature, the overall improvement represented by a new CMIP has become smaller. CMIP6 is better overall than CMIP5 by many measures, but not by so much as to make CMIP5 obsolete. Depending on the specific use case, there may be compelling reasons to use data from CMIP6 or CMIP5, aside from the qualities of the models themselves.

Long answer

Since the first CMIP almost 30 years ago, we can see clear trends in the participating climate models toward higher spatial resolution, greater model complexity, and better simulation of key spatial and temporal features of the climate system. Over time, successive CMIPs have involved more modeling groups from more countries, and more individual models. The emissions scenarios used to drive the models evolve with each CMIP. And as computing power and storage has increased, more runs (projections) are performed, and more output variables at shorter time-steps are archived and made accessible. CMIP6 follows all of these trends with respect to CMIP5, although in many ways the progress is more incremental than it was between the earlier CMIPs.

1) Spatial resolution and model complexity

The evolution of climate models in the last few decades has been marked especially by increases in both spatial resolution (capturing greater detail) and model complexity (representing a greater number of Earth system features and processes).

Global climate models divide the global atmosphere, oceans, and land surface along a grid in both the horizontal and vertical dimensions, creating thousands of 3-D grid boxes. Higher-resolution models can represent more types of atmospheric phenomena directly and better capture the surface topography and its effects on climate. Compared to CMIP5 models, CMIP6 models have generally higher resolution, both horizontally and vertically (Figure 2.1).

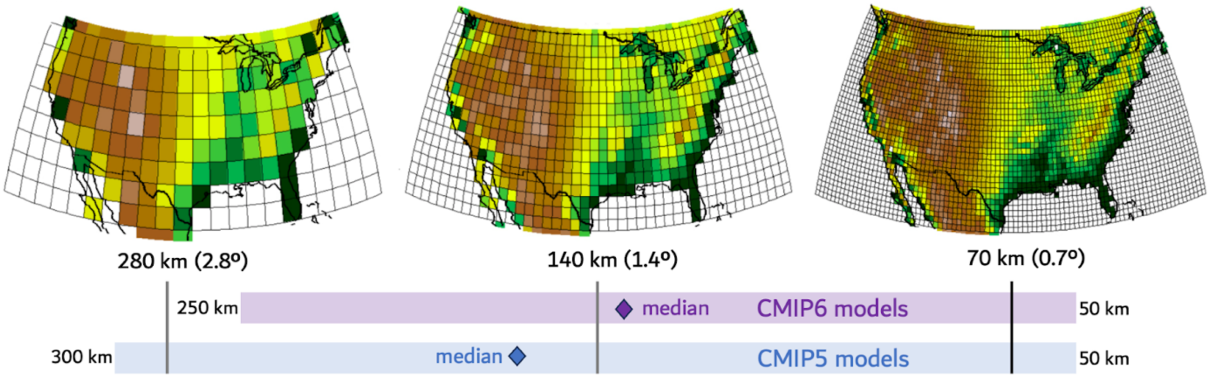

Figure 2.1. Three idealized model grids over the conterminous U.S. showing the effect of increasing the nominal horizontal resolution on the representation of topography (colors). The blue bars below the grids show the range of horizontal resolution of all the models in CMIP6 and CMIP5, respectively, and the median resolution (diamonds). (Grid images: University Corporation for Atmospheric Research (UCAR); resolution data: IPCC AR6 WG1 2021, Ch. 1.5.)

In addition to the dynamics of the atmosphere and oceans, global climate models simulate the land surface (soils and vegetation), ice sheets, sea ice, and the energy and water balances that integrate the various components of the Earth system.

Increasingly, climate models include dynamic atmospheric chemistry, dynamic biological responses, and biogeochemical cycles (e.g., carbon, nitrogen) and their interactions with climate. These models are often classed as Earth System Models (ESMs). ESMs have greater realism, in the sense that they include more processes that are important in the biophysical world, but they may have lower fidelity in replicating historical climate patterns; greater complexity can be a double-edged sword. The CMIP6 model ensemble has a slightly higher proportion of ESMs than CMIP5.

2) Model performance

The accuracy of future projections from climate models cannot be truly evaluated until we get to the future. But the historical performance and reliability of climate models can be evaluated now by comparing their simulations of past climate with observations of climate over the same time period. These comparisons examine both the models' reproduction of climate statistics — averages, ranges, and extremes — and of the features of key climate processes, such as ENSO (El Niño-Southern Oscillation). Keep in mind, however, that models that perform best in historical simulations may not necessarily be the most skillful at predicting future changes in climate as it responds to the unprecedented influences of rapidly increasing greenhouse gas (GHG) concentrations, changes in land use, and changing anthropogenic aerosols.

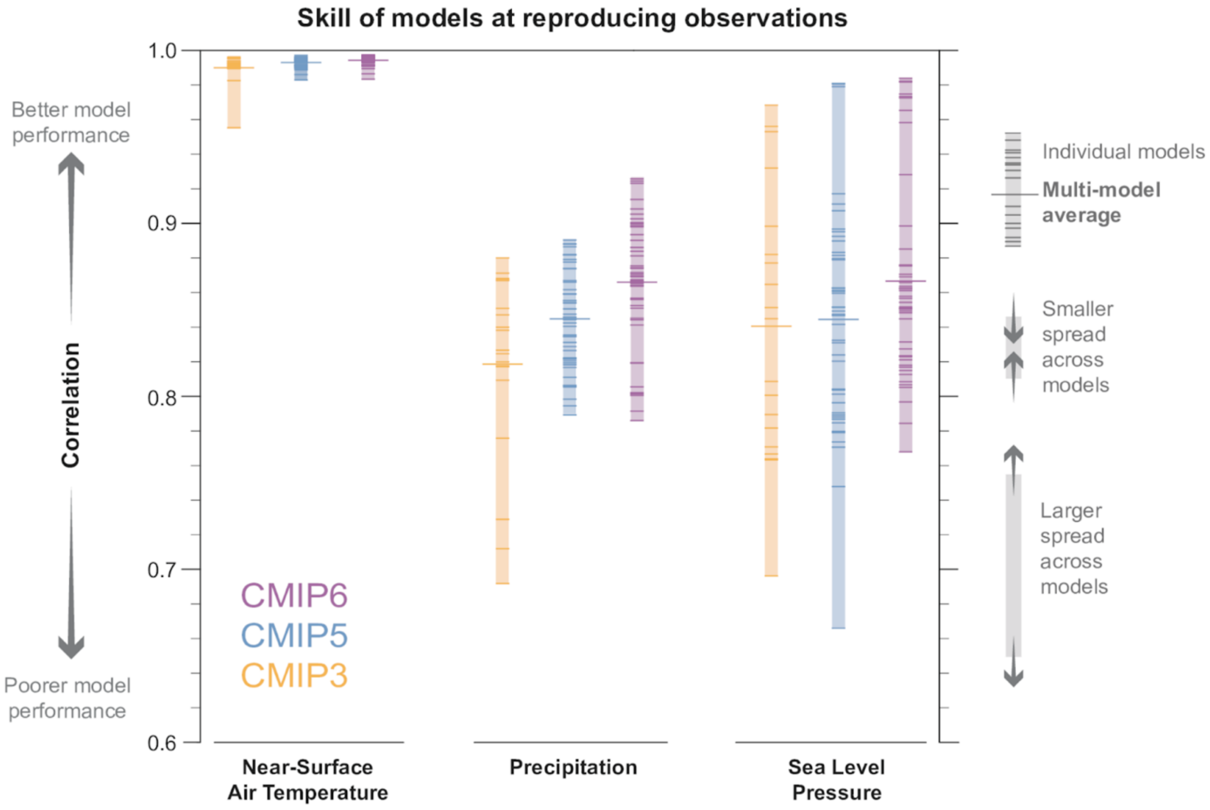

Figure 2.2. Pattern correlations between climate models and observations of three different variables: surface air temperature, precipitation, and sea level pressure, comparing the models from CMIP3 (orange), CMIP5 (blue), and CMIP6 (purple). Individual models are shown with short dashes, the ensemble average with a long dash. For the correlations, the annual averages of the models are compared with the reference observations for the period 1980–1999, with 1.0 representing perfect similarity between the models and observations. (Figure: IPCC AR6 WGI (2021), FAQ3.3, Figure 1)

Evaluations conducted for the IPCC AR6 report indicate that CMIP6 models generally have improved simulations, compared to CMIP5, of the observed *global* spatial patterns of various climate parameters: temperature, precipitation, pressure, winds, incoming and outgoing radiation, humidity, and cloud effects. That said, the range in performance across the CMIP6 models overlaps extensively with the CMIP5 range (Figure 2.2). A model evaluation focused on the Colorado River Basin (Pierce et al. 2021) had similar findings: CMIP6 models generally performed better than CMIP5 models, although the overall best-performing model was from CMIP5. These evaluations also indicate that CMIP6 models are better than CMIP5 models at representing the features and teleconnections of ENSO, although CMIP6 models still have large deficiencies in how ENSO is represented.

3) Emissions scenarios

For each of the last three CMIPs, researchers developed several scenarios, laying out different trajectories of greenhouse gas (GHG) additions to the atmosphere, anthropogenic aerosol emissions, and land-use change – and thus different levels of influence on the climate (i.e., net radiative *forcing*). Each climate model was run under some or all of the emissions scenarios developed for that CMIP (Table 4.1).

The four scenarios (Representative Concentration Pathway; RCP) used for CMIP5 introduced a new nomenclature in which the number (e.g., 4.5) corresponds to the level of radiative forcing in 2100, in watts per meter squared (W/m^2). The Shared Socioeconomic Pathways (SSP) scenarios used in CMIP6 build on the RCPs (see Q3 and Q4); one key difference is that eight different SSPs were used for the CMIP6 modeling, creating a greater diversity of emissions trajectories and potential climate futures.

4) Number of participating modeling centers, models, and model runs

CMIP6 involved a similar number of modeling centers and models as CMIP5, and many more centers and models than CMIP3 (Table 1.1). Of the modeling centers that participated in CMIP3, nearly all also participated in CMIP5 and CMIP6. Similarly, of the modeling centers that were new-to-CMIP for CMIP5, nearly all participated in CMIP6 with upgraded versions of their CMIP5 models.

A clearer difference between CMIP6 and previous CMIPs is the much higher number of model runs (projections) done per model-emissions scenario pairing, and in total, in CMIP6 (Table 1.1). For researchers, this facilitates the creation of single-model ensembles, which can shed light on the relative roles of anthropogenic (forced) change and natural (internal) variability, and otherwise explore drivers of future changes. Such ensembles, however, are beyond the scope and needs of most stakeholder uses of CMIP6. Also note that the available datasets of *downscaled* CMIP6 projections (see Q10) contain many fewer runs than are available in the complete "raw" CMIP6 projection archive.

So, is CMIP6 better?

By most performance measures, *as averaged across the model ensemble*, CMIP6 climate models are better than CMIP5. This is true even with the possibly excessive warming seen in the CMIP6 "hot models" (see Q3). But CMIP6 models are not so much better as to render the output of CMIP5 obsolete. The IPCC AR6 report notes that "despite progress [towards] higher resolution" in CMIP6, "improvements between CMIP5 and CMIP6 remain modest at the global scale."

And for most users, what is "better" needs to be considered in the specific context of the acquisition and application of the climate projections. Few users of climate-model data in the water domain analyze the "raw" CMIP projections; typically, they use downscaled CMIP climate projections that are also run through separate hydrologic models. Downscaling methods and hydrologic modeling have also been evolving alongside the global climate models (see Q10). So any tangible improvements seen in a "CMIP6" hydrology dataset could come from outside the CMIP6 models themselves. But since CONUS[3]-wide downscaling and hydrologic modeling efforts (e.g., those sponsored by US Bureau of Reclamation and the US Army Corps of Engineers) typically lag the release of new CMIP projections by two to four years, the best dataset available *now* for a particular use case may, in fact, be a CMIP5-based dataset.

Further reading:

- Hausfather (2019). *Carbon Brief* Explainer: CMIP6: the next generation of climate models explained.
- IPCC AR6 WGI (2021). FAQ 3.3 | Are Climate Models Improving?
- IPCC AR6 WGI (2021). FAQ 7.3 | What Is Equilibrium Climate Sensitivity and How Does It Relate to Future Warming?

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[3] Most downscaled CMIP5 and CMIP6 datasets for the U.S. really only cover CONUS (the contiguous 48 states); users in Alaska and Hawaii have fewer options.

Q3. What is the CMIP6 hot-model issue, and what are its implications for users?

Short answer

About one-quarter of the CMIP6 models show greater future warming, given comparable emissions scenarios, than even the hottest-running models in the CMIP5 or CMIP3 ensembles. Most of these “hot” CMIP6 models also simulate recent global warming (1980 to 2015) that is greater than the instrumentally observed global warming over that period[4]. Follow-up studies and other evidence suggest that the very high rate of warming seen in the hot CMIP6 models may be physically implausible.

Due to the inclusion of these hot models, CMIP6 shows substantially warmer projected futures, on average, in nearly all locations globally, including in the U.S., than CMIP5 under comparable emissions scenarios. Several methods have been developed to screen or weight the hot models, reducing their influence, as the IPCC authors did in the latest AR6 reports. However, it is not clear that the hot models’ picture of an extremely warm future should be discounted. Also, screening or weighting the hot models may not be appropriate for regional analyses of precipitation and other non-temperature variables. Note that even with the hot models removed, the CMIP6 model ensemble is still somewhat warmer than CMIP5 (see Q7).

Long answer

The hot CMIP6 models have very high values of Equilibrium Climate Sensitivity (ECS) and/or Transient Climate Response (TCR). ECS and TCR are globally calculated benchmarks of how much and how fast the modeled climate warms in response to standardized increases in greenhouse gas forcing. The hot CMIP6 models also tend to overestimate the warming that has been instrumentally observed in the most recent decades (1980–2015). Several studies have investigated why these “hot models” run so hot, and have pointed to how they handle cloud feedbacks and anthropogenic aerosols. It is still not clear if these “hot models” are providing physically plausible views of the future climate, though it is also not clear that they can be discounted completely.

The authors of the IPCC AR6 Working Group I report (IPCC 2021) chose to deemphasize the projections from these hot CMIP6 models, using additional modeling and analysis to develop

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[4] A recent study (Armour et al. 2024) suggests that the observed magnitude of global warming over the last 40 years is not a good metric for judging whether models are “getting it right,” since the observed *spatial* pattern of warming is not replicated by any of the CMIP5 or CMIP6 models. If this is correct, the CMIP6 hot models still appear to be outliers based on other evidence, but the case against them is weaker.

an "assessed" range of future global temperatures. This assessed CMIP6 global warming range ended up being very similar to what the CMIP5 models showed for comparable emissions scenarios.

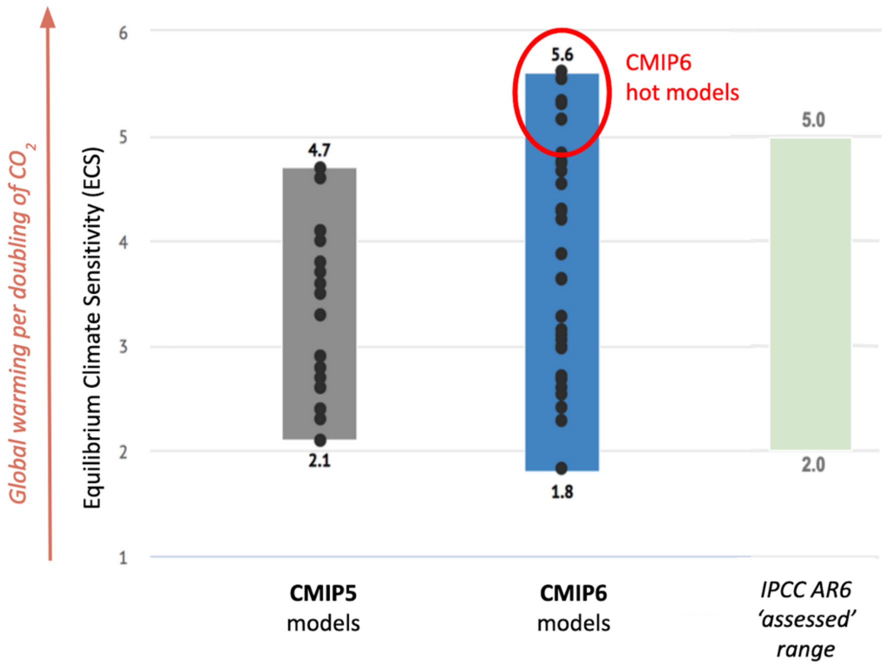

Figure 3.1. Equilibrium Climate Sensitivity (ECS), a measure of a model's globally averaged warming per doubling of CO_2 equivalent, for CMIP5 models and CMIP6 models, compared with the 'very likely' range of ECS as assessed by the IPCC AR6 WG1 authors using multiple lines of evidence. (Modified from original graphic by *Carbon Brief*.)

With CMIP3 and CMIP5, the prevailing approach to considering and treating the various model projections has been called "model democracy": Since we can't be certain today which models have a more reliable take on the future climate, we consider them all, typically equally[5], with one projection per model, or we consider a subset of models that covers the uncertainty across the full ensemble. Sometimes the ensemble gets screened or weighted for particular studies, but usually on the basis of performance specific to that study (e.g., the ability to simulate historical ENSO patterns), not a global metric. By deciding to down-weight the CMIP6 hot models, the IPCC AR6 authors made a significant departure from model

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[5] The Fourth National Climate Assessment (USGCRP 2017) was an exception; the CMIP5 model ensemble was weighted to give higher-performing and more independent models greater weight in the analyses.

democracy, effectively saying one subset of the CMIP models are less trustworthy regarding the rate of future warming.

Enough of the CMIP6 models are "hot" – between 20% and 35%, depending on how "hot" is defined (Figure 3.2) – that retaining all of the hot models in the ensemble leads to warmer depictions of future climate than if they were removed or down-weighted. Unsurprisingly, these globally hot models are hotter in their warming at finer spatial scales as well. This means that local and regional climate-change analyses using all of the CMIP6 models show a meaningfully different future than a comparable analysis with CMIP5 (i.e., under a similar emissions scenario for the same time period) due to the hot-model effect alone. Since warmer temperatures also influence the water cycle in several ways, modeled future water demand and water supply may also be shifted by the hot-model effect, though the direction and magnitude will also depend on the modeled precipitation change for the specific area.

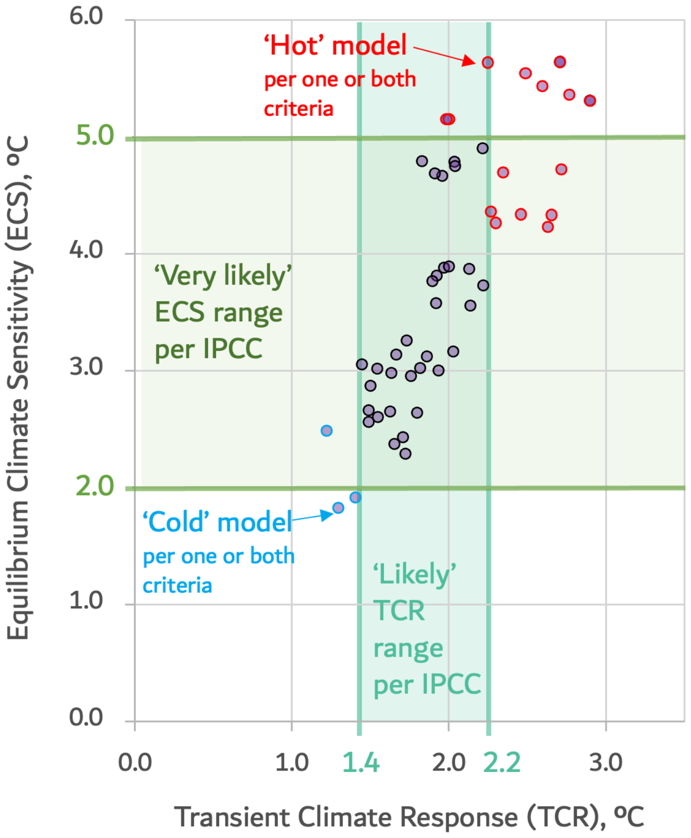

Figure 3.2. The Equilibrium Climate Sensitivity (ECS) and Transient Climate Response (TCR) of 53 climate models in CMIP6, compared with two options for screening criteria for "hot" models based on the IPCC assessed ranges for ECS ("very likely") and TCR ("likely"). (Data: Hausfather et al. 2022a, Nature, Supplemental Information).

As detailed in Q7, screening out hot models (based on TCR) had a relatively minor influence on precipitation averaged across large U.S. regions, but such screening could have greater effects on local analyses.

As of Fall 2024, all providers of raw or downscaled CMIP6 projections (see Q10) include the data from the hot models, leaving it to each user to decide whether and how to limit the hot models' effect on their own analyses. The complex methodology that IPCC AR6 authors used in 2021 to create the "assessed" future global temperatures would be impractical to implement at finer scales, but climate researchers have since proposed alternatives for reducing the effect of the hot models. Below we outline two approaches, the challenges of both, and a recommendation for moving forward.

1) Hausfather et al. (2022a,b) lay out a simple and straightforward screening approach in which projections from those models that fall outside of the "likely" bounds on TCR (1.4°–2.2°C, as judged by the IPCC) are removed from further analyses. This screens out about 40% of the full CMIP6 model ensemble (~20 of ~50 models), including a few models that run too *cold* (Figure 3.1). This approach was employed for the CMIP6 analyses in the *Climate Change in Colorado* report (Bolinger et al. 2024; see Q13). Hausfather et al. also tested three similar screening approaches based on a different set of bounds for TCR, and on two sets of bounds for ECS. Users of the USGS National Climate Change Viewer can choose to display the screened CMIP6 ensemble means based on each of the two ECS bounds, in addition to the full CMIP6 ensemble mean for the selected area.

2) A more complex method put forth by Massoud et al. (2023) uses Bayesian Model Averaging (BMA) to differently weight the CMIP6 models based on where each model's ECS falls on the continuous distribution of ECS likelihood that was developed for the IPCC AR6. No model is completely excluded, but the hot models carry less weight. This approach was used in the recent reports for the Fifth National Climate Assessment (USGCRP 2023b). The USGS National Climate Change Viewer can also show users a weighted CMIP6 ensemble mean based on this approach.

Other researchers have questioned the appropriateness of screening out models based on ECS or TCR thresholds. The values of ECS and TCR are not truly fixed attributes of the models but can vary according to the calculation method. While very high levels of ECS (>5°C) may be unlikely given other evidence, they cannot be ruled out entirely. Furthermore, some of the hot models are also consistently among the better models when evaluated by other global and regional performance metrics (Bloch-Johnson et al. 2022, Rahimpour Asenjan 2023). Discounting the hot models may be inappropriate when analyzing variables other than global or regional temperatures. For analyses of regional precipitation change outside of the polar regions, including in the U.S., weighting hot models does not improve the overall performance of the CMIP6 ensemble and can mislead users by narrowing the apparent range of future precipitation outcomes (McDonnell et al. 2024).

This last caveat is especially relevant to water utilities since the typical workflow for developing future water-supply scenarios requires temperature and precipitation projections from the same set of CMIP model runs. So, if feasible, our recommendation is to first test the sensitivity of the temperature and precipitation output for the area of interest to the presence/absence of the hot models. Using the Hausfather et al. likely-TCR screening method, the screened CMIP6 ensemble can be compared with the unscreened CMIP6 ensemble. Since the screened ensemble is a subset of the full ensemble, this comparison involves little additional effort beyond analyzing the full ensemble. If the screened ensemble shows a large difference in future precipitation change (annual or seasonal) vs. the full ensemble (implying that the hot models' precipitation response is consistently different than the other models), and precipitation is critical to subsequent modeling, then one might consider using the full ensemble. This is an area of active research, so the guidance may change in the coming months and years.

Alternatively, an analysis based on Global Warming Level (GWL; see Q6) sidesteps the hot-model issue, since the amount of future warming is effectively predetermined by the GWL. So a GWL-based analysis can use all of the CMIP6 models regardless of their ECS or TCR.

Further reading:

- Hausfather and Dessler (2024). *Climate Brink* post: Revisiting the hot model problem.
- McDonnell et al. (2024). To what extent does discounting 'hot' climate models improve the predictive skill of climate model ensembles?
- Boyles et al. (2024). Approaches for using CMIP projections in climate model ensembles to address the 'hot model' problem.
- Hausfather et al. (2022b). *Carbon Brief* Guest Post: How climate scientists should handle 'hot models'. (Supporting Information for Hausfather et al. 2022 *Nature* article)
- Massoud et al. (2023). Bayesian weighting of climate models based on climate sensitivity.

Q4. What are the emissions scenarios in CMIP6 and how do they differ from CMIP5 scenarios?

Short answer

The CMIP climate modeling approach uses multiple *emissions scenarios* as model inputs to represent deep uncertainty in the future socioeconomic and policy conditions that will drive the trajectory of greenhouse gas (GHG) emissions and concentrations in the atmosphere over the 21st century and beyond. Each emissions scenario encodes a different degree of anthropogenic influence on the climate (i.e., radiative forcing). Which emissions scenario we end up closest to — and thus the severity of the warming we experience — largely depends on how much additional GHG emissions our collective activities produce. In addition to GHGs, the scenarios specify future changes in land use and anthropogenic aerosols.

For CMIP6, there were eight such scenarios under which the models were run, spanning a broad range of potential future trajectories (Table 4.1). Four of the eight CMIP6 scenarios (SSP1-2.6, SSP2-4.5, SSP4-6.0, and SSP5-8.5) are roughly comparable to the four RCP scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) used in CMIP5.

Long answer

For each CMIP, the climate modeling community adopted a set of *emissions scenarios* whose range is intended to capture the significant uncertainty in how the annual emissions and concentrations of anthropogenic GHGs, as well as other climate forcings like aerosol emissions, land use, and surface reflectivity, will change in the future.

The scenarios developed for CMIP5 were called Representative Concentration Pathways (RCPs), which described trajectories of GHG emissions and concentrations that could arise given plausible future trends in demographic, socioeconomic, technological, and political factors — though these trends were not spelled out in detail. Four RCPs were used to drive the climate models in CMIP5: RCP2.6, RCP4.5, RCP 6.0, or RCP8.5. The numbers refer to the strength of the global climate forcing in 2100 above pre-industrial levels, in watts per square meter (W/m^2) — the extra energy trapped in the climate system by GHGs plus the net effect of other human-caused changes. The higher numbers therefore represent stronger climate forcing and, ultimately, higher global temperatures.

For CMIP6, the demographic, socioeconomic, technological, and political factors were fleshed out in greater detail and distilled into five broad narratives: the Shared Socioeconomic Pathway (SSP) “families” (Figure 4.1). The five SSP families are generally distinguished by different levels of challenges to carbon mitigation and to climate adaptation. For example, SSP1 (“Sustainability”) has low levels of challenges to both, while SSP5 (“Fossil-fueled Development”) has low adaptation challenges but high carbon mitigation challenges.

Within each SSP family, multiple emissions and concentration pathways, each with specific climate forcings, could occur. Thus each of the eight scenarios used to drive the CMIP6

Scenario (*RCP* = CMIP5; SSP = CMIP6)	**Policy and emissions assumptions**
SSP1-1.9	Immediate, aggressive reductions in annual GHG emissions, down to near-zero by 2050, followed by large *negative* emissions (carbon removal). Explicitly developed to depict a pathway in which the global warming level (GWL; see Q6) likely stays below 1.5°C.
RCP2.6 **SSP1-2.6**	Immediate reductions in GHG emissions from today's levels, though not to the extent of SSP1-1.9, and some negative emissions before 2100.
SSP4-3.4	Immediate reductions in GHG emissions from today's levels, though not to the extent of SSP1-2.6; negative emissions after 2085.
SSP5-3.4OS [OS = Overshoot]	Follows the high-end SSP5-8.5 GHG emissions until 2040 (the "overshoot"), then very sharp reductions, and negative emissions after 2065.
RCP4.5 **SSP2-4.5**	GHG emissions peak around 2050 at somewhat higher levels than today, followed by reductions to about half of today's level by 2100.
RCP6.0 **SSP4-6.0**	Similar trajectory to RCP4.5, but with higher GHG emissions at all points. RCP6.0 emissions peak in 2060 and are lower than today's level by 2100. SSP4-6.0 emissions rise more slowly than RCP6.0, peak in 2080, and in 2100 are still higher than today's level.
SSP3-7.0	"Baseline" scenario (i.e., no emissions policies) in which emissions do not rise as dramatically as in the 8.5 scenarios.
RCP8.5 **SSP5-8.5**	*High-end* baseline scenarios[6]; reversion to coal as the primary global energy source, leading to GHG emissions in 2100 that are >3 times today's level. SSP5-8.5 has 20% higher CO_2 emissions than RCP8.5 in the late 21st century, but lower emissions of other GHGs.

Table 4.1. RCPs and SSPs listed in order of their radiative forcing in 2100, and the policy and emissions assumptions behind each RCP and SSP. Tier 1 SSPs (see text) are underlined. (Sources: IPCC AR6 WG1, Ch.1, 2021, Hausfather 2018).

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[6] Since its development in 2010, RCP8.5 has been commonly referred to as a "business-as-usual" (BAU) scenario, but this terminology is now outdated and misleading, since RCP8.5 assumes what would be major shifts away from recent policies and energy use trends. Likewise, "business-as-usual" is not an accurate representation of SSP5-8.5, or even SSP3-7.0.

modeling essentially joins an SSP (the broad societal narrative) with an RCP (a specific trajectory leading to the particular climate forcing), but called simply an "SSP" for convenience (Figure 4.1). Four of the SSPs used in CMIP6 (SSP1-2.6, SSP2-4.5, SSP4-6.0, and SSP5-8.5) map closely to their CMIP5 counterparts (RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively), though their exact emissions trajectories during the 21st century differ, resulting in slightly different climate outcomes for any given year (Figure 5.1). Four new SSPs were introduced for CMIP6 — SSP1-1.9, SSP4-3.4, SSP5-3.4OS (OS = "overshoot"), and SSP3-7.0 — that fill in some gaps between and below the CMIP5 RCPs.

Four of the SSPs were identified as "Tier 1" scenarios, meaning they were a higher priority for the modeling centers producing the climate model runs: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

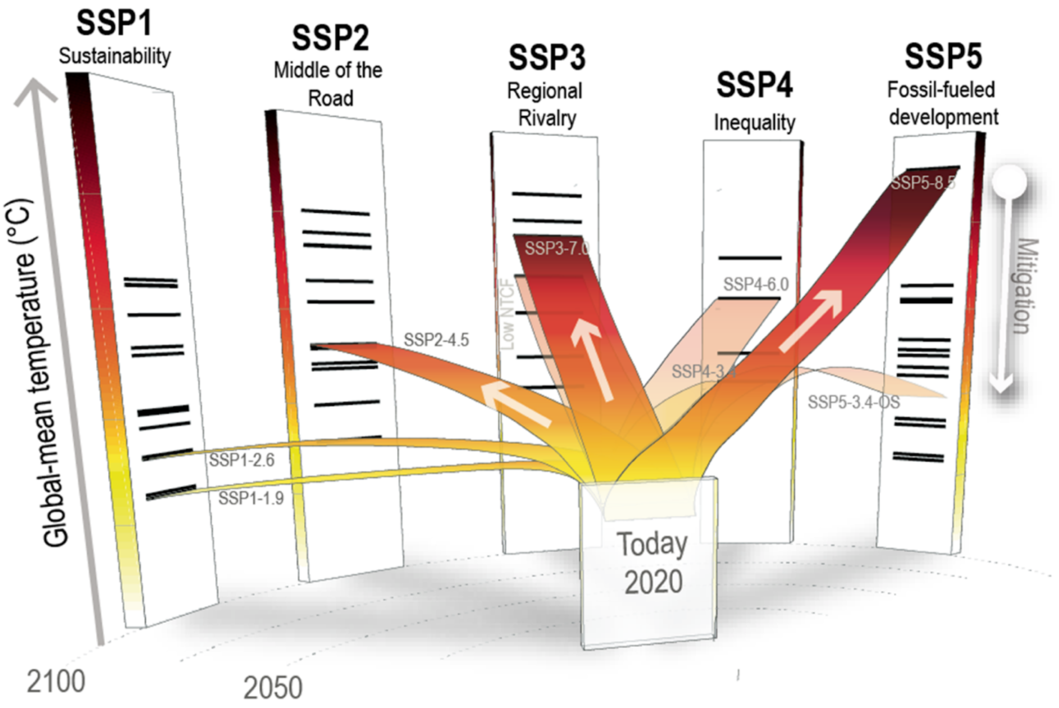

Figure 4.1. The eight SSP emissions scenarios used in CMIP6 (colored bands), their relationships with the five SSP families (pillars), and the average magnitude of global warming associated with each SSP (yellow-red scale on left pillar). (Adapted from IPCC AR6 WGI (2021), Cross-Chapter Box 1.4, Figure 1)

Further reading:

- Hausfather (2018). *Carbon Brief* Explainer: How 'Shared Socioeconomic Pathways' explore future climate change.
- Böttinger and Kasang, DKRZ (no date). The SSP Scenarios.

Q5. Which CMIP6 emissions scenarios (SSPs) should be used in an analysis?

Short answer

The decision of which SSP(s) to use in an analysis should consider several aspects of the scenarios and the intended application, including scenario likelihood, data availability, planning horizon, consistency with previous analyses, and risk tolerance and system vulnerability. Scenario likelihood — which scenarios are more likely to occur, given recent trends in emissions and current policies — is a key consideration for most planning applications. On that basis alone, SSP2-4.5 and SSP4-6.0 would be advisable, followed by SSP4-3.4, with SSP3-7.0 as a potential high-stress scenario. However, there is less output (fewer models/projections) available for SSP4-6.0 and SSP4-3.4 than for SSP2-4.5 and SSP3-7.0. Since the climate outcomes for each SSP increasingly diverge over time, for any analyses focused on later time horizons (~2060 onward) the choice of SSPs is more consequential than for analyses centered earlier in the 21st century.

Long answer

Scenario likelihood

Since the introduction of standardized emissions scenarios about 30 years ago, the IPCC has strenuously avoided attaching likelihoods to the scenarios, instead treating them as equally likely — not unlike how the climate models have been treated. This is understandable; predicting socioeconomic, political, and technological trends is an even more complicated problem than predicting the future climate. But it's hard not to ask, "Which trajectory *are* we on?"

Through the first decade of the 21st century, the answer to that question seemed to be "a high-end scenario." However, since about 2010, the year-on-year increase in global anthropogenic CO_2 emissions has slowed dramatically (Figure 5.1., black line). These CO_2 emissions currently represent about 70% of all anthropogenic greenhouse gas emissions. The trajectory of actual CO_2 emissions through 2023 closely tracks with the RCP4.5, SSP2-4.5, and SSP4-6.0 scenarios, and as of 2023, sits about 20% below the RCP8.5 and SSP5-8.5 scenarios.

This "bending of the curve" reflects recent technological and economic change as well as progress in national and global emissions policies. The global economic crisis associated with COVID caused a temporary downtick in annual emissions in 2020 — closely followed by a recovery-driven uptick — but the bending of the curve was established well before then. From 2000 to 2011, the average annual increase in CO_2 emissions was +2.2%, but from 2012 to 2023, the annual increase was roughly one-fifth of that: +0.4%. The former, steeper, trend, if extended from 2011, would lead to CO_2 emissions exceeding SSP5-8.5 by 2050. The latter trend, however, if extended from 2023, would lead to much lower CO_2 emissions – between the 4.5 and 6.0 scenarios – by 2050.

Accordingly, IPCC AR6 WGI (2021) reported that emissions under current policies, when projected forward with no further actions, are “approximately in line with the intermediate RCP4.5, RCP6.0, and SSP2-4.5 scenarios” through 2070. Figure 5.1 shows comparable projected emissions under current policies from a more recent study (Dafnomilis et al. 2024), along with two other policy scenarios from that study. Again, the 4.5-level scenarios are much more consistent with these “emissions policies of today, or better” pathways than are the 8.5-level scenarios. RCP3-7.0 is a more plausible “high-end” scenario than the 8.5-level scenarios, though according to one analysis, it is toward the outside of the range of plausible outcomes (Moore et al. 2022).

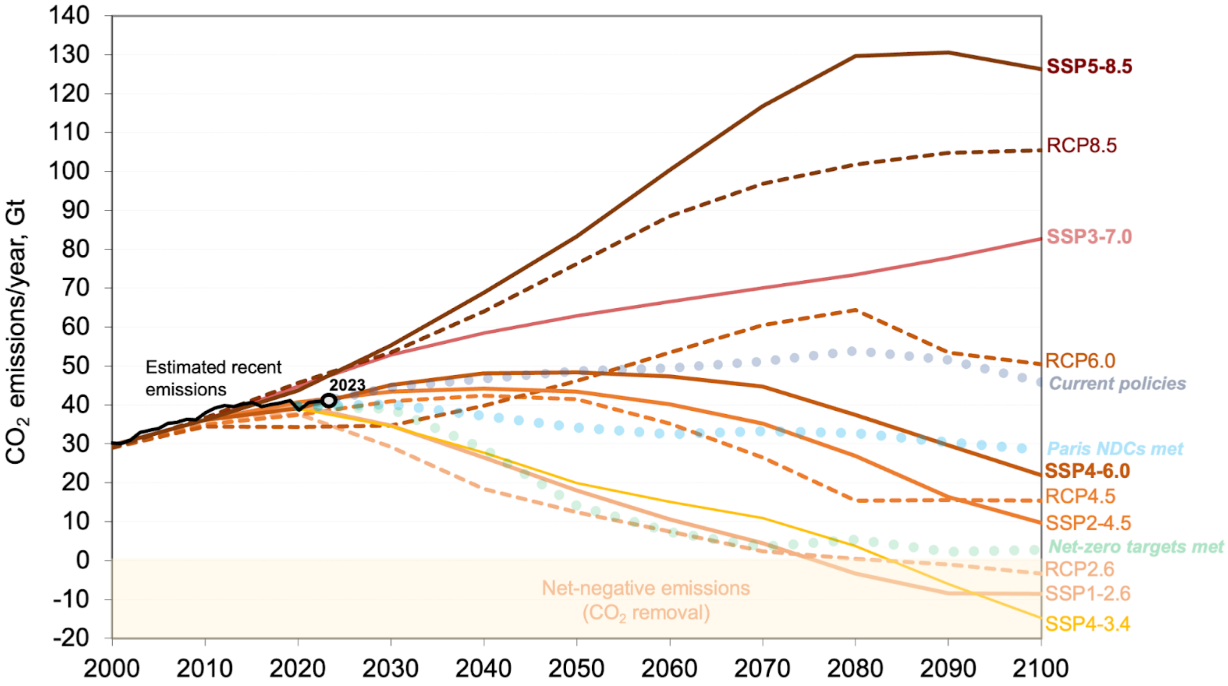

Figure 5.1. Annual global anthropogenic CO_2 emissions through 2100 assumed in the emissions scenarios for CMIP5 (RCPs; dashed lines) and CMIP6 (SSPs; solid lines), projected emissions through 2100 under three different policy pathways based on existing policies, pledges, and targets (bubbled lines), and estimated emissions through 2023 (black line). (Data: RCPs: IIASA RCP Database v2.0.5; SSPs: IIASA SSP Database v2.0; Policy projections: Dafnomilis et al. 2024; Recent emissions: Global Carbon Project 2023)

While current trends in CO_2 emissions are encouraging, high-emission countries may fail to meet targets or even reverse current policies. It is also possible that the atmospheric concentrations of GHGs could end up closer to the 8.5 scenarios despite fossil-fuel emissions remaining on a 4.5-like track. Global methane (CH_4) emissions over the last five years have been greater than ever before; this recent surge has been attributed to higher rates of microbial action (e.g., in wetlands, landfills, and agriculture), likely due to warming, and not fossil fuel production and use or biomass burning (Michel et al. 2024).

Data availability

Due to the enormous computational requirements for running, processing, and storing climate model output, not all of the climate models are run under all of the emission scenarios for each CMIP[7]. In CMIP5, many more models were run under RCP4.5 and RCP8.5 than under RCP2.6 or RCP6.0. In *downscaled* CMIP5 datasets derived from a subset of the "raw" CMIP output, the disparity was even greater; some widely used datasets (e.g., LOCA, MACA) contained projections only under RCP4.5 and RCP8.5.

For CMIP6, the data availability situation is better, at least with respect to the raw projections: Comparably large sets of the models — about 50 — were run under each of four "Tier 1" SSPs (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). But many fewer of the models — only 11 to 18 — were also run under the other four SSPs. The downscaled CMIP6 datasets that have been produced so far have reflected the greater availability of raw projections; e.g., the LOCA2 (CMIP6) dataset has roughly equal numbers of models/projections (~24) under three SSPs (SSP2-4.5, SSP3-7.0, and SSP5-8.5).

Planning horizon

Over shorter time horizons (<25 years, out to ~2050), the range of total radiative forcing across the SSPs, and thus the range of modeled global and regional climate changes, is much less than later in the century. So the CMIP6 model ensemble under a single, mid-range SSP (3.4, 4.5, 6.0) will cover much of the range of possible climate outcomes seen across all of the SSPs. Over longer time horizons (>40 years, ~2065 and beyond), the radiative forcing levels of the SSPs diverge sharply, creating a much broader range of possible climate outcomes across the SSPs. Analyzing the CMIP6 ensemble under two or more SSPs would then be more appropriate to capture more of that range.

Consistency with previous CMIP-based analyses

Another consideration would be consistency with previous CMIP-based analyses. Using emissions scenarios that are considerably different from those used in past work (e.g., CMIP5 RCPs) may result in stakeholder confusion. Many — if not most — CMIP5-based vulnerability analyses in the water sector used RCP4.5 and RCP8.5 as a rather sensible pairing of a "lower" and "higher" scenario. SSP2-4.5, as noted earlier, is comparable to RCP4.5. Likewise, SSP5-8.5 is a close match to RCP8.5 — but both 8.5 scenarios are now seen as highly unlikely to occur, as described above.

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[7] For example, the Community Earth System Model version 2 (CESM2) as run for CMIP6 requires roughly 500,000 CPU-hours to produce a single run from 2015 to 2100. Even if the NCAR Cheyenne supercomputer were fully utilized, this one run would take ~3 hours. In total, the CESM2 runs for CMIP6 generated a total of >2 petabytes (>2,000 terabytes) of data.

Risk tolerance and system vulnerability

If the consequences of a system failure are so severe that even rare events under a low-likelihood climate future need to be characterized and incorporated into planning (i.e., the system has low risk tolerance), then SSP5-8.5 generally produces the greatest climate changes and impacts at any given time horizon. But if the consequences of system failure are less dire, then the more probable scenarios assuming lower emissions may be sufficient for risk assessment.

Note that the most extreme projected climate outcome or event is not guaranteed to be generated by the most extreme emissions scenario. This is particularly true for shorter-horizon projections (<2040), where natural variability, which is expressed in the differences between multiple runs from the same model under one emissions scenario, can overshadow the differences between emissions scenarios. Similarly, for certain types of events the low-emissions scenario may have the most extreme outcome. For example, for rain-on-snow flooding events, a low-emissions scenario in which snowpacks persist out to 2100 may show larger extremes than a high-emissions scenario in which snow ultimately disappears.

Further reading:

- ClimateData.ca. Understanding Shared Socio-economic Pathways (SSPs).
- Hausfather (2019). *Carbon Brief* Explainer: The high-emissions 'RCP8.5' global warming scenario. *Web explainer.*

Q6. What are Global Warming Levels (GWLs) and how do they correspond to the CMIP6 emissions scenarios?

Short answer

Global Warming Levels (GWLs) are a relatively new approach for analyzing and communicating regional-to-local climate changes that sidesteps the questions of exactly *when* those changes might happen and under what emissions scenarios. GWL-based analyses are typically displayed as maps or tables. They show the spatial pattern of projected future changes in a particular variable (e.g., extreme precipitation) that are associated with a particular increment of globally averaged warming, such as +2°C (+3.6°F). GWL-based analyses can provide a versatile framework for risk assessment but may require some adaptation to use in more traditional long-range planning centered on a specific time horizon.

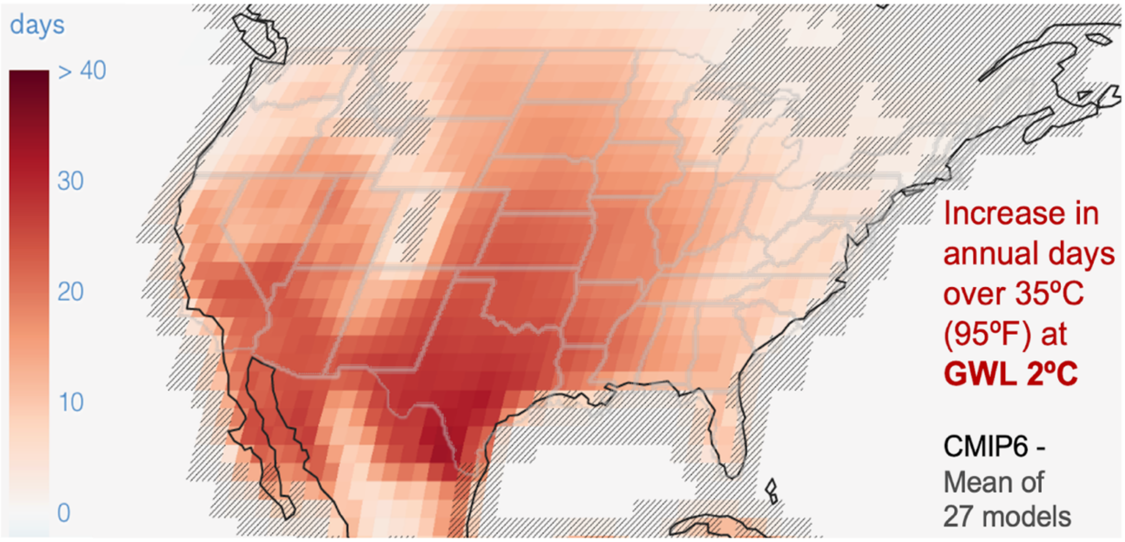

Figure 6.1. Example of a Global Warming Level (GWL) analysis: Projected future increase in the number of days per year over 35°C (95°F) at a GWL of 2°C, based on the mean projection from 27 CMIP6 models. (Source: Modified from *IPCC WGI Interactive Atlas*)

Long answer

In 2021, the IPCC AR6 report featured a relatively new approach to communicating regional-to-local climate changes and impacts: the Global Warming Level (GWL). The Fifth National Climate Assessment (NCA5) followed suit, prominently using GWL-based graphics to convey nationwide, state, and local impacts in the reports and the NCA Interactive Atlas. While GWLs were introduced to the world alongside the CMIP6 projections, they can be used to analyze CMIP5 projections as well.

So what is a GWL? It is defined by the globally averaged surface temperature change, in degrees Celsius, relative to a "pre-industrial" baseline (1850–1900)[8]. The standard, or "core," GWLs used in the AR6 and NCA5 reports are 1.5°C, 2°C, 3°C, and 4°C. (The GWL is sometimes written with only the number: 1.5, 2, etc.) It's crucial to note that the world has *already* warmed by ~1.2°C relative to the pre-industrial baseline — so we are now most of the way to GWL 1.5°C, over halfway to GWL 2°C, and so on. Producing a GWL map involves determining when[9] each model's globally averaged temperature reaches a given GWL (e.g., 2°C), extracting the changes in the variable of interest for that time period, repeating for all models in the ensemble, and then taking all of the models' values for each gridbox and plotting the ensemble mean.

Instead of asking, "What regional and local changes are projected to occur by year *X* under emissions scenario *Y*?", a GWL-based analysis asks, "What regional and local changes are projected to occur at such time that the *globally* averaged temperature change reaches *Z*?" The questions "when" and "which emissions scenario" still have some bearing in GWL analyses, since the higher GWLs (3°C, 4°C) are more likely to be reached by a model after more time elapses (e.g., by 2080 vs. 2050) and under higher emissions scenarios.

There is a wide range of timing for the different models to reach a given GWL; the timing for each model is roughly proportional to that model's ECS and TCR (see Q3). So each GWL analysis or map reflects many different time periods, varying by model, in order to provide a unified, composite picture of what global-to-local climate changes look like *at that GWL*.

GWLs can be translated, at least roughly, to the familiar analyses based on time and emissions scenarios. Table 6.1 shows when the CMIP6 ensemble *mean* reaches all four GWLs. For each emissions scenario, the table provides the average future year *when* a given GWL is reached by the CMIP6 models. It takes longer to reach the higher GWLs, especially under lower-emissions scenarios.

Why use a GWL-based analysis instead of a more traditional one? The GWL approach avoids any disagreements about which emissions scenarios to use. It also allows for easier communication about future changes; stakeholders do not need to be briefed on emissions scenarios to get a sense of what a 2°C warmer world will look like. Another advantage is that GWLs reinforce a core concept of climate change: Most changes in the climate system, at all spatial scales, are scaled to the magnitude of the global temperature change. As global temperature increases, so do other changes and impacts. GWLs also simplify the mapping of

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[8] This particular baseline was used so that the GWLs are in sync with how international climate-policy goals have long been expressed, such as the "well below 2°C" goal of the 2015 Paris Agreement.

[9] To be more precise: when the center year of a 20-year running average of that model's globally averaged surface temperature crosses the GWL value (e.g., 2°C).

the spatial pattern of changes and impacts. A single map under GWL 2°C essentially collapses and conveys the information found in multiple maps of different time slices and under multiple emissions scenarios.

GWL	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
1.5°C	*~2028*	*~2028*	*~2028*	*~2026*
2°C	*~2075*	*~2047*	*~2044*	*~2040*
3°C	Doesn't reach	*~2095*	*~2070*	*~2061*
4°C	Doesn't reach	Doesn't reach	*~2093*	*~2077*

Table 6.1. The approximate year that the 10-year-averaged CMIP6 ensemble mean under each of the four main emissions scenarios (SSPs) reaches each of the four GWLs. (Data: *IPCC WGI* Interactive Atlas, extracted from the Global Warming Plot tool)

A final advantage of GWLs was mentioned earlier, in Q3: There is no need to screen or weight CMIP6 for hot models, since by definition the temperature change in a GWL is fixed. The fact that a hot model will reach any given GWL sooner is irrelevant to the analysis of local and regional changes at that GWL.

Water-utility planning is typically centered on specific time horizons. GWL-based analyses — in which the time horizon is hazy — are at first glance less suited for such planning than traditional year-and-scenario analyses (e.g., 2070 under SSP2-4.5). But GWLs can provide a more versatile way to frame risk analyses. For example, one can first assess what, say, a 2°C warmer world would mean to a water supply, and then look back at a set of climate models to examine, according to those models and emissions scenarios, *when* those changes might happen. This type of analysis would make for easier integration of projections from future CMIPs once a table like Table 6.1 is generated. Climate-impact researchers have also used a hybrid approach of "GWL + year." For example, a NOAA-led multi-agency study (Sweet et al. 2022) assessed the magnitude of U.S. sea level rise at five different GWLs. For each GWL, the analysis included only data from those models that crossed that GWL during the end-of-century period (2081–2000).

Further reading:

- Goldenson (2023). Cal-Adapt Blog: Understanding Climate Futures through the lens of Global Warming Levels.
- Climatedata.ca (no date). Introduction to Global Warming Levels.
- Climatedata.ca (no date). More About Global Warming Levels.
- UK Met Office (2024). Climate Dashboard: Indicators of Global Warming

Q7. Does CMIP6 show different future climate outcomes for the U.S. than CMIP5, given comparable emissions scenarios?

Short answer

For projected future temperature and precipitation for the U.S., the differences between the CMIP5 and CMIP6 ensemble means are relatively small compared to the overlap between the two ensembles of global models. The respective *spatial* patterns of projected temperature and precipitation change for CMIP5 and CMIP6 are also very similar. (Robust comparisons of fine-scale hydrologic changes between CMIP5 and CMIP6 are not feasible with existing datasets as of Fall 2024.)

That said, in the preliminary comparisons described below, the CMIP6 ensemble mean and median show greater warming for the major U.S. regions than the mean and median for CMIP5. This also holds true for most locations in the U.S., even after screening or weighting models for the *hot-model issue* (Q3). The differences in projected temperature are large enough that CMIP6-based analyses may show appreciably greater temperature-related vulnerabilities — and potentially greater hydrology-related vulnerabilities as well — than the equivalent CMIP5-based analyses.

Long answer

As of Fall 2024, no robust and systematic comparisons between CMIP5 and CMIP6 at a scale suitable for regional U.S. interests have yet been published. Such “apples-to-apples” comparisons between the CMIP ensembles are inherently difficult to construct[10]. The information in this response is drawn from preliminary analyses done specifically for this FAQ, using data and interactive graphics from two readily accessible sources[11] of CMIP projections:

- Raw (original-resolution) projections - IPCC Interactive Climate Atlas
    - CMIP5: 28 models
    - CMIP6: 34 models (temperature); 32 models (precipitation)
    - Maps of ensemble-average change across the U.S.

- Raw (original-resolution) projections - Copernicus Interactive Climate Atlas
    - CMIP5: 23 models

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[10] Our original intent was to compare downscaled CMIP6 (LOCA2) with downscaled CMIP5 (MACAv2), both available at the county level (see Q10), but the different downscaling methods and different-sized model ensembles made that infeasible.

[11] These two portals have some tradeoffs for their ease of accessing and analyzing the data. The Copernicus Atlas contains projections from fewer models (~24) than most archives of raw CMIP (typically, ~30–36 models). The IPCC Atlas has more models, but the data output formats do not permit screening of the CMIP6 hot models like the Copernicus Atlas does.

- CMIP6: 24 models (and Likely TCR-screened: 14 models)
- 3 regions/divisions of North America (mainly the U.S.): Eastern, Central, Western

Note that while the figures below only show comparisons for 4.5-level emissions scenarios, the CMIP5-CMIP6 differences seen under the 4.5 scenarios are very similar to the patterns of CMIP6-CMIP5 differences under the 2.6 and 8.5 emissions scenarios, respectively.

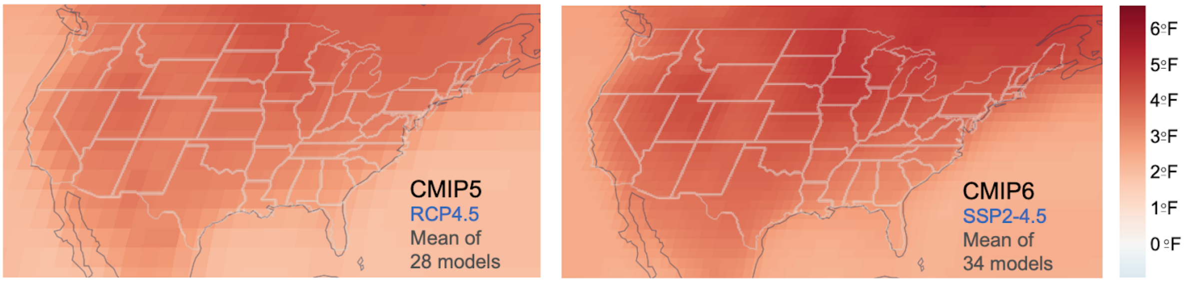
Temperature and precipitation (raw) - ensemble mean changes

For annual temperature (Figure 7.1.a), the ensemble mean CMIP5 and CMIP6 changes have a very similar spatial pattern across the U.S.:

- Lesser warming in all coastal areas and the Southeast
- Greater warming in the upper Midwest and Northeast
- A “hotspot” over the Great Basin

However, the mean CMIP6 warming is greater than the CMIP5 mean in all parts of the U.S., especially the interior West and the upper Midwest. (Note that this CMIP6 ensemble is not screened or weighted to account for the hot models; see Q3.)

a) Change in Annual **Temperature** under 4.5 emissions scenarios, 2041-2060 vs. 1981-2010



b) Change in Annual **Precipitation** under 4.5 emissions scenarios, 2041-2060 vs. 1981-2010

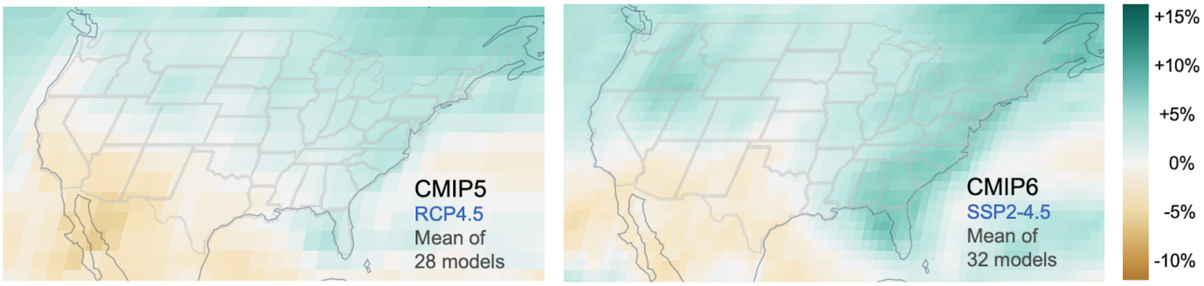


Figure 7.1. Ensemble-mean projected changes for the 2041–2060 period in (a) average annual temperature and (b) average annual precipitation under 4.5 emissions scenarios in CMIP5 (left) and CMIP6 (right). (Maps: *IPCC WGI Interactive Atlas*)

Before turning to precipitation, we need to note that precipitation is much more difficult to model under climate change at regional scales than temperature, and there is correspondingly *greater uncertainty* in projections of the future change in precipitation. For annual precipitation (Figure 7.1.b), the mean CMIP5 and CMIP6 future changes do have a similar pattern across the U.S.: decreases in the far Southwest and Texas, and increases or no change elsewhere.[12]

But the mean CMIP6 change is shifted slightly wetter than CMIP5 almost everywhere, with the largest wet shifts in northern California, the Northwest, and the Southeast. Given that CMIP6 is overall warmer, it is not surprising that it is generally wetter. The amount of water vapor in the atmosphere tends to increase with warmer temperatures, due to the Clausius-Clapeyron relationship, which typically leads to greater precipitation on daily to annual timescales, except where changes in atmospheric circulation patterns counterbalance the basic water-vapor increase, such as over Mexico and the far southwestern U.S.

For seasonal precipitation (Figures 7.2.a, 7.2.b), the mean CMIP5 and CMIP6 changes have broadly similar patterns in all four seasons. There are greater pattern differences in summer and fall. For example, in fall CMIP6 shows decreased precipitation over the Great Plains while CMIP5 shows little change or increased precipitation.

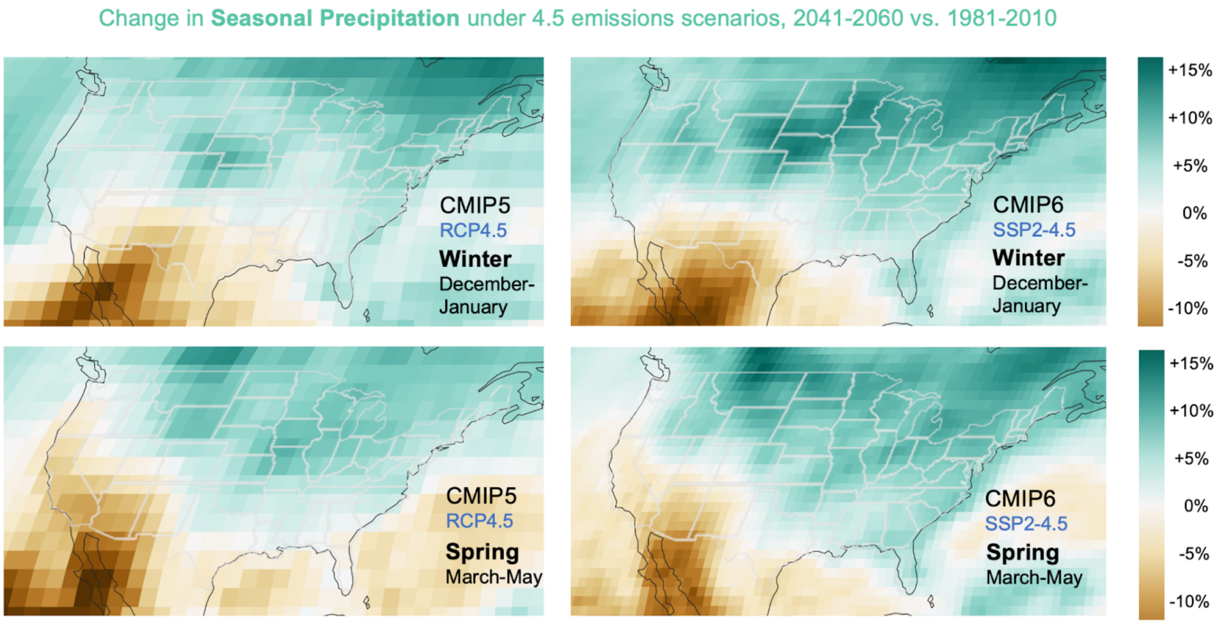


Figure 7.2.a. Ensemble-mean projected changes for the 2041–2060 period in average seasonal precipitation (Winter, Spring) under 4.5 emissions scenarios in CMIP5 (28 models; left) and CMIP6 (32 models; right). (Maps: *IPCC WGI Interactive Atlas*)

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[12] The CMIP5-CMIP6 similarity in spatial patterns of precipitation change over the U.S. was also noted in Almazroui et al. (2021).

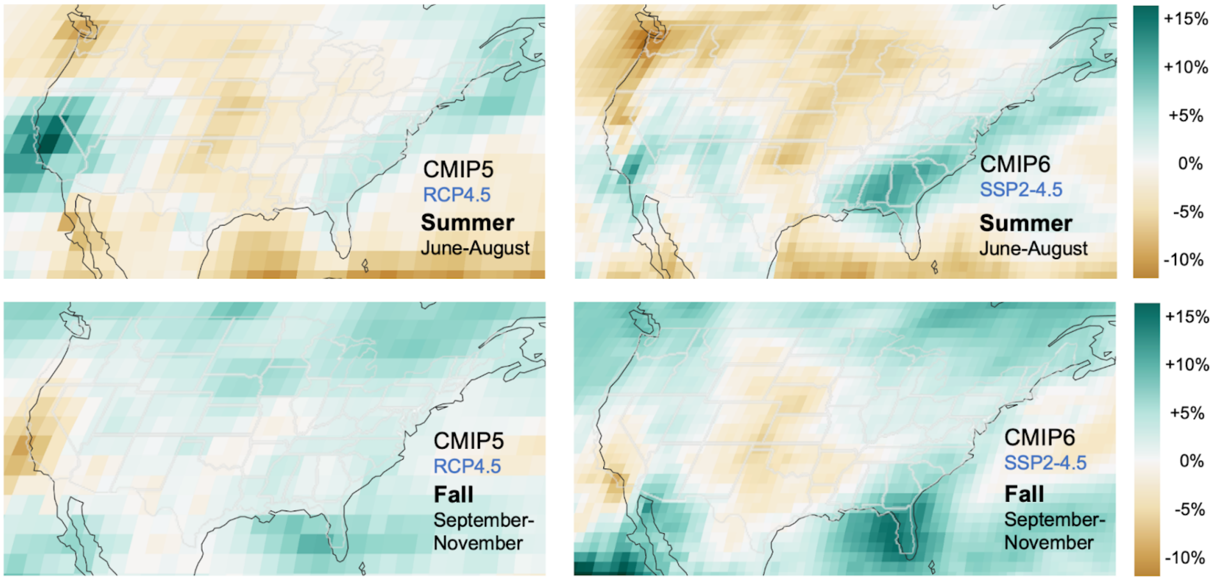

Figure 7.2.b. Ensemble-mean projected changes for the 2041–2060 period in average seasonal precipitation (Summer, Fall) under 4.5 emissions scenarios in CMIP5 (28 models; left) and CMIP6 (32 models; right). (Maps: *IPCC WGI Interactive Atlas*)

Temperature and precipitation (raw projections) - changes by region

Here we are comparing projected temperature and precipitation across *three* model ensembles: (1) CMIP6 unscreened, (2) CMIP6 screened for hot models using Likely TCR, and (3) CMIP5, as averaged across three regions of the U.S. (Figure 7.3).

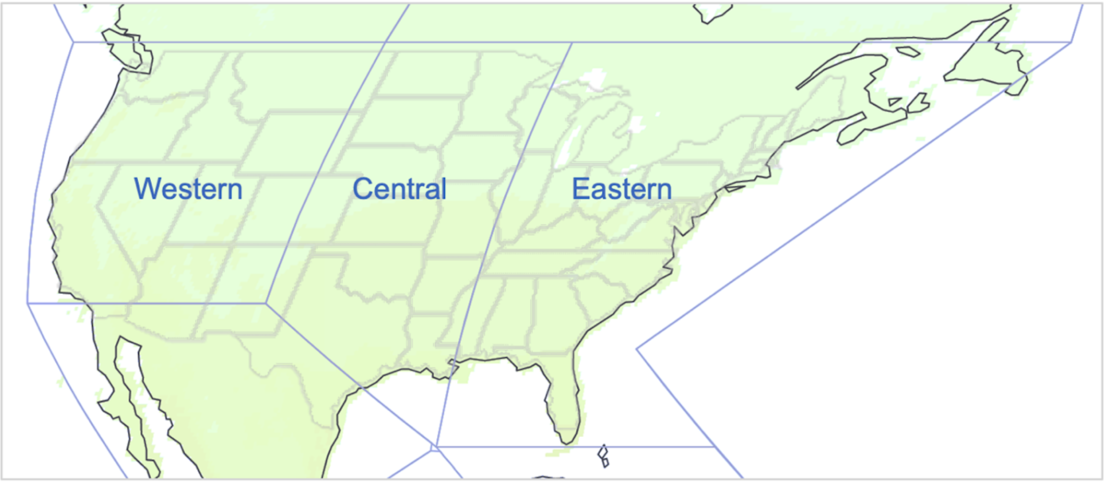

Figure 7.3. Regions of the U.S. (and portions of Canada) as delineated by the IPCC for the AR6 reports, and also used in the *IPCC Interactive Atlas* and *Copernicus Interactive Atlas*.

The changes in annual average temperature by 2055–2084 (Figure 7.4) show that the ensemble median warming in *unscreened* CMIP6 is greater than in CMIP5 in all three regions, by 0.8°F to 1.2°F. The largest CMIP5-CMIP6 difference is in the Central region. This mirrors what is seen in the map in Figure 7.1.a, although there are fewer models in the ensembles shown in Figure 7.4.

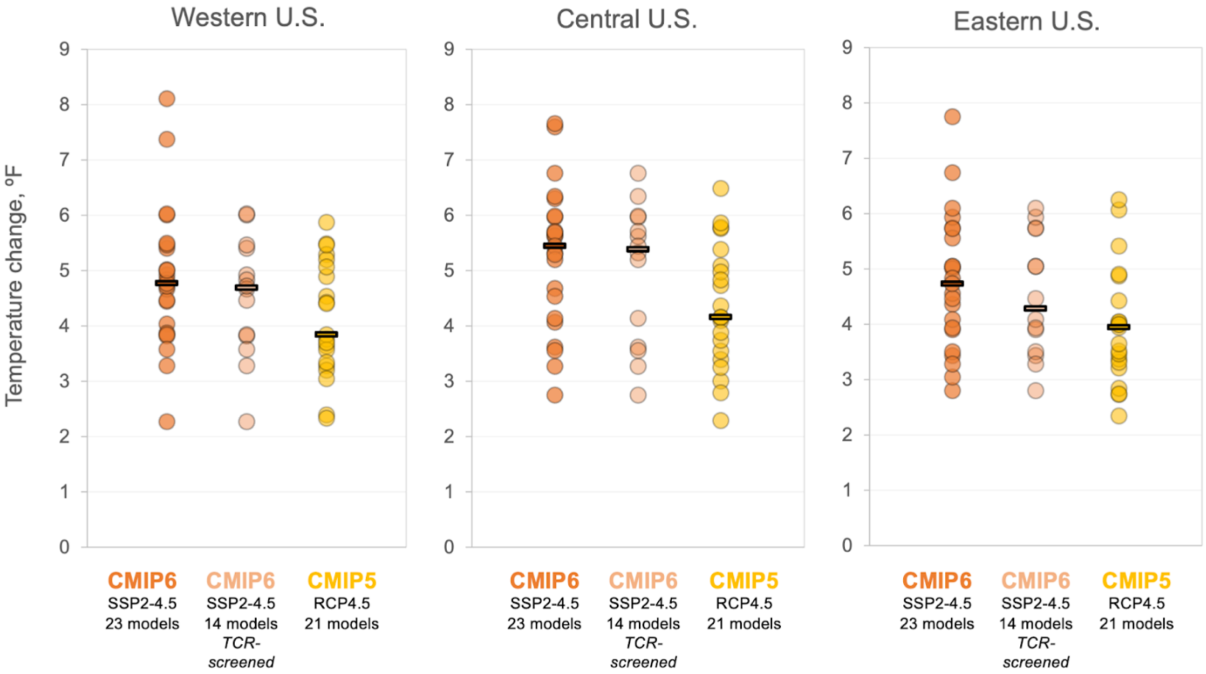

Figure 7.4. Projected changes in annual average temperature for 2055–2084 (vs. 1981–2010) in the Western, Central, and Eastern regions of the U.S. from a CMIP6 model ensemble (orange), a TCR-screened CMIP6 ensemble with hot models removed (light orange), and a CMIP5 ensemble (yellow), under comparable 4.5 emissions scenarios. The individual model projections are shown as circles; the ensemble median is shown with a black bar. (Data: Raw projections from *Copernicus Interactive Climate Atlas*)

After screening based on "likely TCR" (see Q3), the ensemble median warming in CMIP6 is reduced by ~0.1°–0.5°F, mainly due to the removal of several "hot" models at the high end of the range. The ensemble mean of screened CMIP6 is still ~0.5°–0.7°F warmer than CMIP5 in each region, although without the high-end hot models, the range of projected changes for TCR-screened CMIP6 almost entirely overlaps with CMIP5.

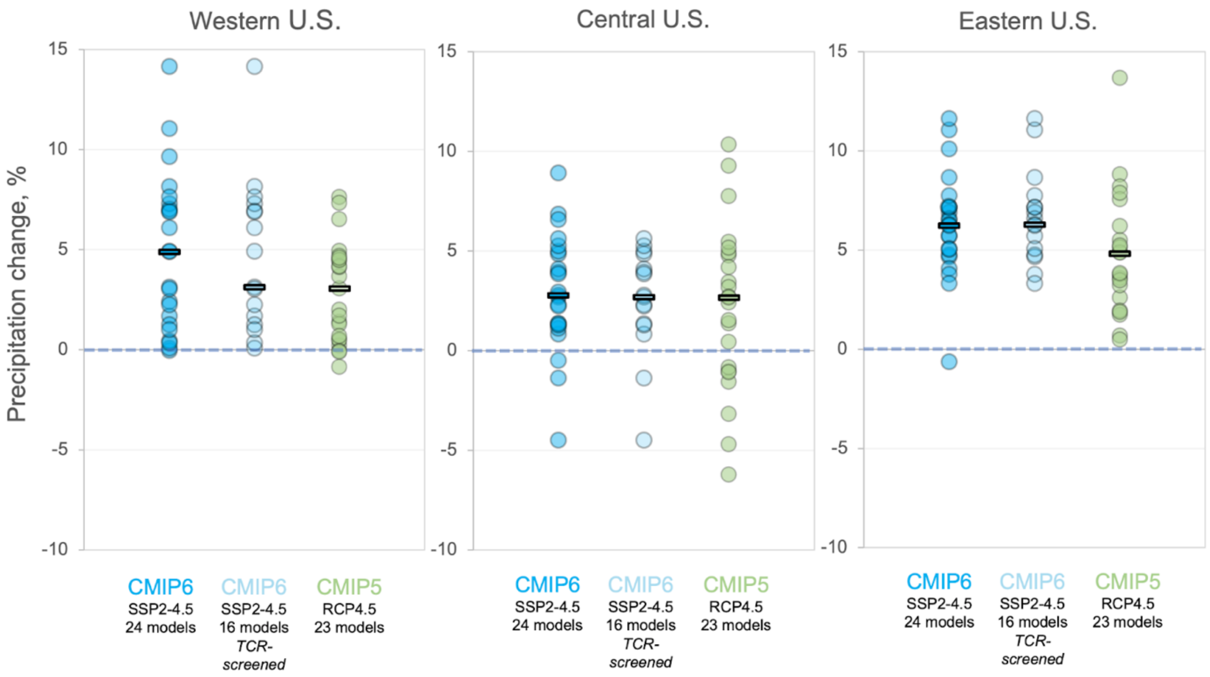

Figure 7.5. Projected changes in annual average precipitation for 2055–2084 (vs. 1981–2010) in the Western, Central, and Eastern regions of the U.S. from a CMIP6 model ensemble (blue), a TCR-screened CMIP6 ensemble with hot models removed (light blue), and a CMIP5 ensemble (green), under comparable 4.5 emissions scenarios. The individual model projections are shown as circles; the ensemble median is shown with a black bar. (Data: Raw projections from *Copernicus Interactive Climate Atlas*)

For precipitation (Figure 7.5), the ensemble medians in unscreened CMIP6 are marginally wetter (by ~1%) in the western and eastern regions. The overall CMIP6 range in those two regions is noticeably shifted wetter than in CMIP5. There is little difference between CMIP6 and CMIP5 in the central region. The median changes in the TCR-screened CMIP6 ensembles are very similar to the unscreened CMIP6 ensembles in all three regions, although the ranges are reduced by screening. (Note that screening out hot models when analyzing local or regional *precipitation* change, as shown here, may be inappropriate; see Q3.)

Extremes of heat

A reasonable assumption is that the CMIP6 projections, being overall warmer than CMIP5 in terms of average annual temperatures, should also show a shift toward even more frequent and intense high temperature extremes than is seen in CMIP5. A preliminary examination of the IPCC Interactive Climate Atlas plots indeed shows that for raw, unscreened CMIP6, metrics of extreme temperature for the U.S. (days above 35°C/95°F; days above 40°C/104°F) are appreciably higher than for CMIP5, under comparable emissions scenarios. Note that downscaled projections are better suited for analyzing weather extremes, but as of Fall 2024, such analyses have not yet been conducted for temperature extremes.

An analysis by Wehner (2020) based on GWLs shows no appreciable difference in the change in future heat extremes for the U.S. between CMIP6 and CMIP5 at any given GWL; that is, when the effect of the CMIP6 hot models is removed. This suggests that the change in extreme temperatures scales to the change in mean temperature in similar ways in the CMIP6 models and CMIP5 models.

Extremes of precipitation

The Clausius-Clapeyron relationship (warmer = more water vapor can be held in air) is especially consequential for extreme precipitation events, since these events involve water vapor levels that are near their seasonal and geographic limits. Since CMIP6 projects more warming overall than CMIP5, raising those limits even further, we would expect CMIP6 to show more intense/frequent extreme precipitation events than CMIP5. A preliminary examination of raw, unscreened CMIP6 vs. CMIP5 (using the IPCC Interactive Atlas) shows that for the U.S, CMIP6 has slightly larger extreme one-day and five-day precipitation events than CMIP5, under comparable emissions scenarios.

As with temperature extremes, downscaled projections are much better suited for analyzing trends and patterns in precipitation extremes. Pierce et al. (2023) examined extreme one-day precipitation events in the U.S. in LOCA-downscaled projections and found *significantly* larger future increases in those events in CMIP6[13] (LOCA2) than in CMIP5 (LOCA), for comparable emissions scenarios. LOCA2 uses an improved historical precipitation analysis for the downscaling, and an improved bias-correction scheme, compared to LOCA. The extent of the differences in extreme precipitation they found — greater than the differences seen between raw CMIP6 and raw CMIP5 — may be partly due to those improvements.

Streamflow

As of Fall 2024, there is only one high-resolution (<25-km) dataset of physics-based hydrologic model output for the U.S. using CMIP6 climate projections: the DOE ORNL SECURE dataset (Kao et al. 2024a, 2024b), described further in Q10. This dataset contains future hydrologic projections, using the VIC and PRMS models, based on only seven CMIP6 models, so the findings (e.g., mean streamflow change for a given watershed) may not be representative of a larger CMIP6 ensemble. Likewise, this dataset is difficult to compare with CMIP5-based hydrology projections. An earlier version of this dataset (Kao et al. 2022) showed mean projected future increases in annual runoff across nearly all of CONUS; however, the underlying mean precipitation change, from six CMIP6 models under SSP5-8.5, was wetter than we see in a larger CMIP6 ensemble under SSP2-4.5 (Figure 7.1.b).

Sea level rise

Global mean sea level (GMSL) is rising on decadal and longer timescales due to the thermal expansion of ocean water with warming, and to increasing runoff from ice sheets and

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[13] The CMIP6-LOCA2 ensemble used by Pierce et al. was not screened for hot models.

glaciers. The trend of regional to local relative sea level (RSL) will vary from the GMSL mainly due to vertical land motions (uplift/subsidence), as well as ocean circulation patterns and atmosphere-ocean dynamics (Sweet et al. 2022). While global climate models can reasonably simulate the thermal-expansion component of future GMSL rise and the ocean and atmospheric dynamics affecting RSL, they generally lack the features and processes needed to quantify the ice-melt component of GMSL, and they don't include vertical land motions. Furthermore, there is deep uncertainty in the future contribution of ice-sheet dynamics to sea level rise (Kopp et al. 2023).

Accordingly, comprehensive projections of future sea level rise require modeling and data sources above and beyond the CMIP climate model output. The most recent multi-agency assessment of sea level rise for the U.S. (Sweet et al. 2022) incorporates CMIP6 model output, observed gage trends (to capture vertical land motion), and several methods of projecting future ice-sheet changes, within a GWL-linked scenario framework. While the projections in Sweet et al. (2022) differ from the previous, CMIP5-based, U.S. sea level assessment (Sweet et al. 2017), that is mainly due to new sources of ice-sheet modeling. A study by Hermans et al. (2021) isolated the impact of CMIP6 vs. CMIP5 models on sea level projections by repeating the methods of the CMIP5-based assessment of GMSL in the IPCC AR5 report — which had a similar framework to the U.S. assessments — this time using CMIP6. They found that the projected rise in GMSL by 2100 was modestly increased (by +3% to +7%) when using the CMIP6 ensemble, which is consistent with the greater global and regional warming seen across the CMIP6 models.

Further reading:

- Almazrouhi et al. (2021). Projected Changes in Temperature and Precipitation Over the United States, Central America, and the Caribbean in CMIP6 GCMs. (Has only limited comparisons with CMIP5)
- Interagency Sea Level Change Task Force. (2024). U.S. Sea Level Change and National Sea Level Explorer.

Q8. How does the level of uncertainty in CMIP6 compare with CMIP5?

Short answer

There are several sources of uncertainty in any set of future climate and hydrology projections at local-to-regional scales (e.g., emissions scenario uncertainty, model uncertainty, natural variability uncertainty). An especially important one to consider in comparing CMIP6 with CMIP5 is *model uncertainty*, sometimes called *structural uncertainty*. The model uncertainties in projected future temperature can be characterized by the spread of projected changes across the model ensemble. By this measure, model uncertainties seen in CMIP6 are of similar magnitude to CMIP5, given comparable emissions scenarios and comparably sized model ensembles. However, the total uncertainty in a CMIP6-based analysis of local climate and hydrology changes could differ from the uncertainty in a CMIP5-based analysis for multiple reasons beyond the climate models themselves. Also, consulting a larger number of models will typically reveal greater uncertainty.

Long answer

In any given ensemble of future climate or hydrology projections, uncertainty arises from several sources and aggregates as a combined uncertainty (Figure 8.1). The primary sources are the unknown level and rate of future emissions (see Q4 & Q5), the imperfect structure of climate models, and the difficulty of disentangling (modeled) natural variability from the long-term change signal in model projections.

In general, for longer time horizons (>2040), the largest sources of uncertainty in regional temperature projections are emissions scenarios and model structure. For regional precipitation and streamflow projections, model structure is the largest source of uncertainty, with emissions scenarios and natural variability as secondary contributors.

The sources of uncertainty in CMIP5 and CMIP6 are further compared below.

Emissions scenario uncertainty

As detailed in Q4 and Q5, for CMIP5 there were four emissions scenarios (RCPs), ranging from RCP2.6 to RCP8.5. Nominally there was a range of ~6 W/m2 of radiative forcing between the lowest and highest scenarios by 2100. For CMIP6, there were eight scenarios, ranging from SSP1-1.9 to SSP5-8.5, a slightly larger range of ~6.5 W/m2. If one were to use *all* scenarios *and* consider them equally, there would be greater emissions uncertainty inherent in CMIP6 than in CMIP5 (Lehner et al. 2023).

However, compared to when the RCPs were developed and CMIP5 data were first released, there is much more information available to help constrain the potential trajectories of future GHG emissions, including the recent inflection in the trajectory of CO_2 emissions and the further enactment of national and global policies restricting GHG emissions (see Q5). Thus, it is now reasonable to discount the highest SSP scenarios (SSP3-7.0, SSP5-8.5) when using

CMIP6, which will reduce the effective scenario uncertainty (Moore et al. 2022, Lehner et al. 2023). But regardless of the CMIP and the specific set of emissions scenarios, emissions uncertainty increases over time and is much larger in 2100 than in 2050.

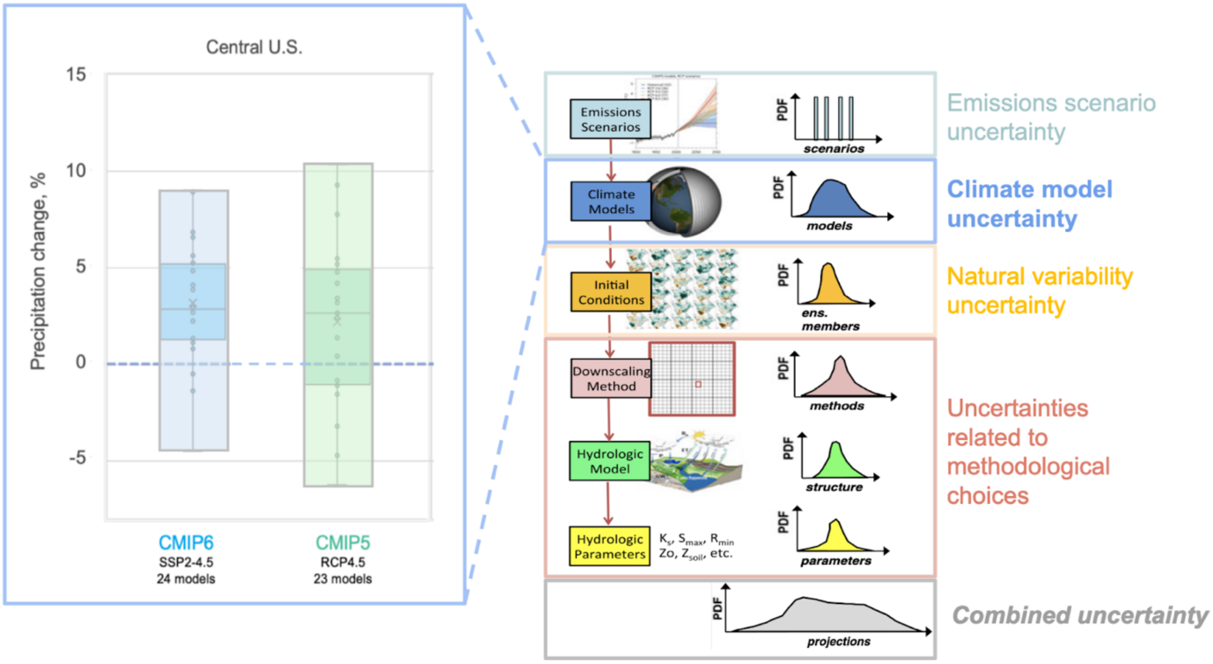

Figure 8.1. Schematic showing the uncertainty ("PDF" or range of possibilities) associated with each of several steps in the climate impact modeling chain. Climate model uncertainty — as reflected by the spread across a model ensemble (inset) — is only part of the combined or total uncertainty. (Inset: Data from Copernicus Interactive Climate Atlas; Right side of figure: Modified from Figure 1, Clark et al. 2016, "Characterizing Uncertainty of the Hydrologic Impacts of Climate Change.")

Model uncertainty

The spread of projected changes across an ensemble of climate models under a given emissions scenario and for a given time period provides a rough gauge of the *model uncertainty*. Different models represent key climate processes in different ways, and we don't know which model structure provides the most accurate depiction of the future. This is why results from multiple models (i.e., a model ensemble) should be considered in any analysis. Like emissions scenario uncertainty, model uncertainty increases over the 21st century, especially for temperature. The differences between models in their inherent sensitivity to GHG changes (ECS and TCR; see Q3) lead to increasingly divergent temperature outcomes.

In Q7, we saw that for change in annual temperature in the three U.S. regions, the spread of the unscreened CMIP6 ensemble under a 4.5 scenario for a mid-century period is greater than the spread of the CMIP5 ensemble. But when the hot CMIP6 models are screened out (via TCR-based screening), the CMIP6 spread is reduced, becoming comparable to the CMIP5 spread (Figure 7.4). This is consistent with the findings of a more sophisticated global analysis of uncertainties in CMIP5 and CMIP6 (Lehner et al. 2020).

For change in annual precipitation, the spread of the unscreened CMIP6 ensemble is somewhat greater than the CMIP5 ensemble in the western region, somewhat smaller in the central region, and comparable in the eastern region (Figure 7.5)[14]. After TCR-based screening for hot models, the CMIP6 spread is reduced in all three regions. This is mainly due to the exclusion of some hot models that are "warm and wet" and show large projected increases in regional precipitation.

As climate models improve over time in terms of model resolution and representation of historical climate patterns, it seems reasonable to expect that model uncertainty (spread across the models) should decrease, with increasing agreement among the different modeled futures for each CMIP. But moving from CMIP3 to CMIP5 to CMIP6, we have not seen a systematic reduction in model uncertainty over time. The principal reason for this is that while the direct radiative effect of an increment of greenhouse gases (e.g., a doubling of CO_2) can be precisely quantified, the ultimate effect of that increment on global temperature and the other aspects of the climate system depends on a number of processes and *feedbacks*, most importantly those associated with clouds, water vapor, aerosols, sea ice, and ice sheets. At regional scales, land-surface processes and feedbacks become increasingly important.

The progress in quantifying the individual effects and net effect of some of these feedbacks has been painfully slow, especially with clouds. And over time, additional processes and feedbacks are included in climate models. Every time a model incorporates a new element, the number of *parameters* in the model increases. So even if the quantification of each parameter is improved over time, the increasing complexity can effectively cancel out those improvements.

Natural variability uncertainty

It is obvious that the climate experienced in a given location varies from one year to the next and from one decade to the next. What is not as obvious is that climate models, as realistic simulators of the behavior of the climate system, will also simulate this natural (or *internal*)

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[14] A global analysis by Wu et al. (2022) found that for future precipitation changes through 2100, *globally averaged* CMIP6 model uncertainty was larger than in CMIP5. They did not offer an explanation for the increased uncertainty, but the CMIP6 ensemble they used (26 models) was larger than the CMIP5 ensemble (21 models), which could explain some of the increase.

variability of the climate system across multiple temporal and spatial scales. Thus, embedded in every projected time-series from a single climate model run is a sequence of natural variability unique to that run.

When we want to calculate the magnitude of change (i.e., between a historical period to a future period) in a climate model projection, this simulated natural variability becomes "noise" that is difficult to separate from the anthropogenically forced signal. This is a much bigger problem for precipitation — in which natural variability is large compared to the forced signal — than for temperature, which has the opposite characteristics. Even when a 20-year or 30-year averaging period is used to "dampen" natural variability, it is still present in analyses of precipitation change.

Natural variability uncertainty does not increase over time, and there is very little difference between CMIP5 and CMIP6 in the magnitude of natural variability uncertainty. Natural variability and its uncertainty do become more prominent as one moves from global to regional to local spatial scales. It can be helpful to gauge the size of natural variability uncertainty for the area and variable(s) of interest by examining multiple runs from the same model under one emissions scenario.

Additional modeling uncertainties

Many uses of CMIP projections by water utilities involve downscaled climate projections and hydrologic modeling using the downscaled projections as inputs. These "downstream" modeling steps introduce new uncertainties at each step that are akin to (climate) model uncertainty: All representations of the physical world are imperfect, and it is hard to discern which one is "right" (or more so than the others). These additional uncertainties are becoming better understood and are more frequently explored in analyses; e.g., by comparing results from multiple hydrologic models. So a utility's CMIP6-based analysis could well show a broader range of outcomes than a previous CMIP5-based analysis if more of these downstream modeling uncertainties are explicitly treated in the new analysis.

Further reading:

- McGuire et al. (2021). Ch. 9: Uncertainties. Pp. 353-369 in *West-Wide Climate and Hydrology Assessment*.
- Lukas et al. (2020). Ch 11.8: Interpreting climate change-informed hydrology in light of multiple uncertainties. Pp. 441-446 in *Colorado River Basin Climate and Hydrology: State of the Science*.

Q9. Should CMIP6 or CMIP5 be used in a new analysis? Should existing CMIP5 analyses be updated with CMIP6?

Short answer

If a new analysis of climate projections is required, then it makes sense to use CMIP6, assuming the desired type and spatial scale of CMIP6-based data are accessible. Downscaled hydrologic model output based on CMIP6, for example, is not yet widely available. It is not usually necessary, however, to update existing CMIP5-based analyses just for the sake of using the latest CMIP projections. That said, updating an analysis to CMIP6 also provides an opportunity to implement enhancements in other data-processing and modeling steps.

Long answer

There are several considerations that might lead one to use CMIP6 in new or updated analyses, rather than use CMIP5 — or to not conduct a new or updated analysis at all. Most of these considerations are outside of the CMIP6 projections themselves: The intended purpose of the analysis, what existing analyses show, whether the analysis requires hydrologic or other modeling, capacity (e.g., who will undertake the analysis, what will it cost, will it meet the decision timeline), how the information will help inform the decision, and stakeholder expectations and consistency in communications. Below are some helpful questions to ask.

Will the differences between the CMIP5 and CMIP6 climate outcomes matter to the system of interest?

Before one commits to an updated or new analysis, it is worth asking whether climate futures for a given region or location would be different enough between CMIP5 and CMIP6 to appreciably shift the *analyzed* risk of the system vulnerabilities of greatest concern. This presumes that from previous CMIP-based analyses, one already has some idea of the sensitivity of the system to temperature change and precipitation change as it relates to the risks of interest.

In the comparisons shown in Q7, CMIP6 generally shows warmer and slightly wetter futures (on an annual basis) than CMIP5 for comparable emissions scenarios — though with more overlap between the two sets of CMIP futures than not. And CMIP5-CMIP6 differences are larger for some regions of the country than others. So once appropriate CMIP6 data are analyzed, some local vulnerability metrics, like heat stress on workers or the size of the 10-year/1-day precipitation event, might show greater risk in CMIP6 vs. CMIP5, while others, like average water-supply yield, might not shift or could show *less* risk under CMIP6.

In principle, the USGS National Climate Change Viewer, which includes separate viewers for downscaled CMIP5 (MACAv2) and downscaled CMIP6 (LOCA2), can provide a first look at the localized differences between CMIP5 and CMIP6. However, given the difference in downscaling methods, this is not an apples-to-apples comparison. The downscaled CMIP5 (LOCA) displayed in the Climate Explorer portal is better suited for comparison with CMIP6

(LOCA2) in the NCCV. Unfortunately, the two portals analyze and display the projections using different future time periods, making direct comparisons difficult.

Is fine-scale hydrologic modeling or other impact modeling needed?

As of Fall 2024, there are only a few options for CMIP6-based, fine-scale hydrology datasets covering the U.S. The DOE ORNL SECURE daily hydroclimate dataset (Kao et al. 2024; see Q7) uses physics-based hydrology models, but only has output from seven climate models. The LOCA2-Monthly Water Balance Model dataset (available through the USGS National Climate Change Viewer) has output from 23 climate models but uses a relatively simple water-balance model at only a monthly time-step. More CMIP6 hydrology datasets for the U.S. will be forthcoming in the next one to two years (see Q12).

For other modeled impacts (e.g., wildfire-hazard, ecosystem, health), the situation is much the same. Few CMIP6-based datasets are available now, leaving one with the choice of using currently available datasets, doing custom modeling, or waiting for new datasets. Water utilities may have a predetermined update cycle for long-range plans (e.g., every five years) that would preclude waiting another year or two for new datasets to emerge. In that case, a CMIP5-based analysis that takes advantage of an existing downscaled dataset may be the best course of action.

Are the existing CMIP5-based analyses otherwise up to date?

The CMIP5 model ensemble is still considered to be usable and reliable. If existing analyses using CMIP5 are still valid in other respects, there is less need to redo them with CMIP6. If one or more of the following conditions is not met, then a new analysis with CMIP6 might be justified:

- The emissions scenarios (RCPs) are consistent with current guidance on handling emissions-based climate uncertainty (see Q5).
- If downscaled CMIP5 was used, the downscaling method was *not* the Reclamation variant of BCSD, which has been found to have a widespread wet bias in projected precipitation, especially in the western U.S.
- The hydrologic models and any other models used to translate the CMIP5 projections into system impacts are still considered state-of-the-art. (Note that different and equally valid hydrologic models can produce substantially different hydrologic futures, given the same climate inputs.)
- The understanding of the water system's vulnerabilities and their representation in system model(s) has not changed significantly since the CMIP5 analyses were performed.

Is there an expectation that the very latest science be used in analyses?

While the climate-science community still gives CMIP5 data its overall stamp of approval, it may be hard to explain to stakeholders why one would use the previous generation of climate model output in a *new* analysis. If there is a strong expectation that the latest science be used, using CMIP6 can be justified if other considerations are met. But as noted in Q2, while CMIP6 may be “the latest science,” it’s not unequivocally better than CMIP5 for all applications.

Finally, it is important to remember that models are, and always will be, imperfect representations of the real world. They are most valuable when they allow people to think and work outside the box of the observed hydrology and stress-test their system in novel but meaningful ways. This can be done through multiple types of inputs (CMIP climate model output, climate-informed stochastic hydrology, paleoclimate reconstructions, etc.). Updating the CMIP data used in planning can help provide additional stress-testing, as long as it does not cause information overload or “analysis paralysis.”

Q10. What CMIP6 datasets are available for visualization and/or download, and where can they be accessed?

Short answer

The primary ESGF[15] archive of original-resolution (*raw)* CMIP6 projections is available to any user, but the archive is enormous and challenging to navigate, and the data files are very large. Alternatively, the CMIP6 portals on Amazon Web Services and Google Cloud host the ESGF data files and allow users to perform analyses in the cloud, but these portals require high skill in data handling as well. More manageable partial archives of raw CMIP6 projections are available from three other portals where users can visualize the data prior to downloading, with options for spatial and temporal clipping and averaging of the data.

A handful of higher-resolution, *downscaled* CMIP6 datasets are also available for global or U.S./North American domains. These are value-added products based on subsets of the primary raw CMIP6 archive and are produced by research groups outside of the CMIP framework. Only one downscaled dataset (LOCA2) is currently accessible through a visualization portal (USGS National Climate Change Viewer; the other datasets are download-only). More options for downscaled data are likely to become available soon.

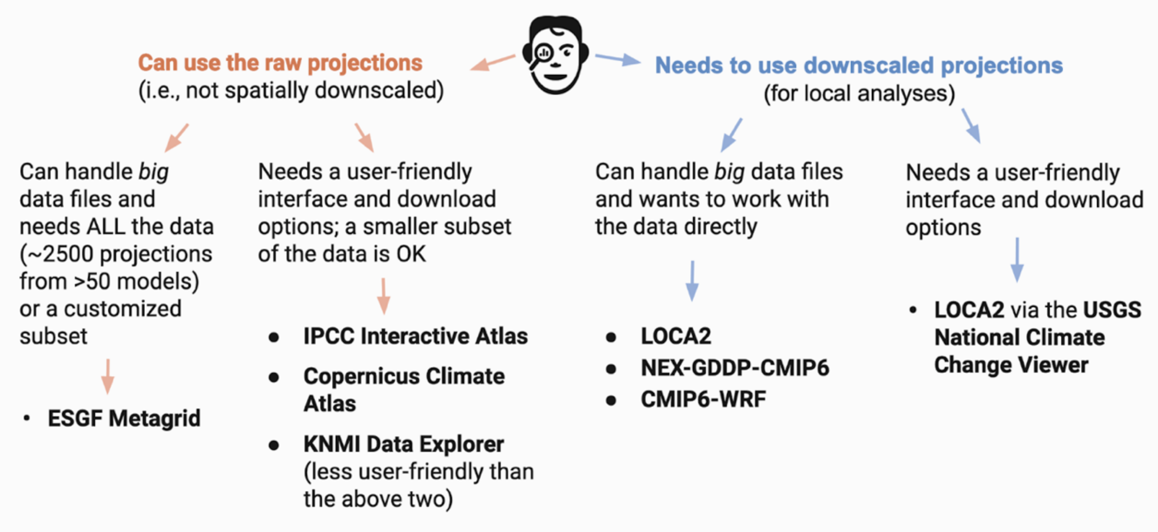

Figure 10.1. Schematic showing selected CMIP6 datasets that are currently available as of Fall 2024, as matched with user needs and characteristics. See "Long answer" below for more details and links to these datasets.

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[15] ESGF = Earth System Grid Federation, an international collaboration that manages the decentralized database for handling climate science data, with multiple petabytes of data at dozens of federated sites worldwide.

Long answer

Raw projections

The direct or *raw* output of the GCMs is appropriate for analyses at the global scale down to the broad regional scale (e.g., southeastern U.S.). The raw projections can be useful for rapid evaluation of how future changes in temperature and precipitation differ between CMIP5 and CMIP6, without the potential complication of the downscaling method — which can, on its own, lead to appreciable differences between downscaled CMIP5 and CMIP6 projections.

The available archives of raw CMIP6 projections also have the advantage of being larger and more diverse (e.g., more models, more individual projections) than most datasets of downscaled CMIP6 projections. Note that from model to model, there are differences in which of the SSPs were run with that model, how many ensemble members were run for each SSP, and which climate variables were archived. The raw projections have not been *bias-corrected*, unlike downscaled datasets, so any analyses with raw projections should use a *delta method*, in which the values of a climate variable averaged over a model's historical period are subtracted from that model's average over the future period of interest.

The original output format for CMIP data is NetCDF (*.nc*) files, which can handle multi-dimensional data (typically latitude, longitude, and time) in a portable, self-describing format. Each unique combination of a model, an emissions scenario (SSP), an ensemble member (i.e., a *run* or *realization*), and a climate variable is archived in its own NetCDF file (see Q10-Sidebar for details on file naming conventions). The file will have data values for each time step of the run (daily or sub-daily) over the period 2015–2100 for most future projections, for each of thousands of gridpoints globally. Each raw CMIP6 file is ~2GB to ~15GB (for daily data), depending on the climate model's spatial resolution. Hundreds of files may be needed for even a basic analysis, so if the data are being downloaded for local computing, an automated process (e.g., Python script using OPeNDAP) and many terabytes of storage will be needed.

Another option for accessing and working with raw CMIP6 files is cloud computing via Amazon Web Services or the Google Cloud, both of which host CMIP6 portals and data "buckets" with both the ESGF NetCDF files and Zarr data stores (compilations of NetCDF files). Cloud computing eliminates the need to download and store data files locally but typically requires subscription fees and a steep learning curve.

The NetCDF and CSV files for *processed* raw CMIP6 data available from the KNMI Climate Explorer, Copernicus Climate Atlas, and IPCC Interactive Atlas described below (e.g., clipped to a specific spatial region and/or time period) are much smaller than the original files and require no scripting to obtain data for multiple models in a single operation.

Full CMIP6 raw archive

The full archive includes all models, all emissions scenarios under which those models were run, all ensemble members, and all modeled variables that were saved from the runs, as *daily* or *sub-daily* data. Recommended only for experienced big-data-handlers familiar with CMIP data.

- **ESGF Metagrid**
    - From 48 to 53 models run under each of four main emissions scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5); 11 to 18 models run under the other four SSPs; most model/emissions combos run multiple times. See list of ESGF holdings.
    - Search tool to identify and download any subset of CMIP6 data files
    - Script desirable for downloading more than a few dozen files
    - Most of the CMIP6 files in ESGF can also be downloaded through the Globus service.

- **Amazon Web Services (AWS) - CMIP6**
    - ESGF CMIP6 data are available in two S3 Buckets: One bucket with the original, separate, netCDF files, and one bucket in which the netCDF files have been packaged into Zarr data stores.
    - AWS data holdings can be used in cloud computing or downloaded for local use.

- **Google Cloud - CMIP6**
    - ESGF CMIP6 data are only in Zarr data stores.
    - Google Cloud data holdings can be used in cloud computing (i.e., a Jupyter notebook running in Google Colaboratory) or downloaded for local use.

Portals with partial and processed CMIP6 raw archive

Most models, two emissions scenarios, one projection per model (or one to several), selected variables, *monthly* data (with some daily analyses). Recommended for most users.

- **IPCC Interactive Atlas**
    - All data spatially regridded to a 1° (~100-km, ~60 miles) grid
    - SSPs (# Models): SSP2-4.5 (34); SSP3-7.0 (30)
    - Variables[16]: T, dT, P, dP, Sn, W; 23 total
    - Easy to select and visualize data; very limited options for spatial slicing but can also grab ensemble mean values for any gridcell
    - Downloads (netCDF) of projected variables are limited to ensemble means for region, though users can *visualize* individual models.

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[16] T = temperature (monthly); dT = daily metrics of T; P = precipitation (monthly); dP = daily metrics of P; W = wind; H = humidity; ET = evapotranspiration; SM = soil moisture; Q = runoff; D = drought indices; PU = surface air pressure; SN = snow; SR = incoming shortwave radiation; LR = incoming longwave radiation. Note that there are often multiple variables in each category, e.g., daily min/max/average T.

- **Copernicus Climate Atlas**
  - All data spatially regridded to a 1° (~100-km, ~60-mi.) grid
  - SSPs (# Models): SSP1-2.6 (22) SSP2-4.5 (23); SSP3-7.0 (22); SSP5-8.5(28)
  - Variables[16]: T, dT, P, dP, W, ET, SM, Q, D, SR, LR; 30 total
  - Easy to select and visualize data; same limited options to define U.S. regions as IPCC Atlas; can grab ensemble mean values for any gridcell
  - Downloads (CSV) of projected variables have separate columns for each model.

- **KNMI Climate Explorer**
  - Data at each model's native resolution; can also be spatially regridded to a 1.875° x 1.25° (~135-km, ~85-mi.) grid
  - SSPs (# Models): SSP1-2.6 (40); SSP2-4.5 (40); SSP3-7.0 (36); SSP5-8.5(41).
  - Variables[16]: T, P, PU, SR; 6 total
  - More difficult to select, visualize, and download data than the above two portals, but *many* more user options; any lat-long box can be selected, or user can upload a spatial mask for custom regions
  - Downloads of projected variables have separate NetCDF file for each model.

Downscaled projections

Even though the spatial resolution of raw CMIP6 projections is generally finer than that of CMIP5, it is still too coarse to capture the topographic complexities of mountainous and coastal parts of the U.S. and their effects on climate, and too coarse to be used as inputs for regional climate-impact modeling (e.g., watershed hydrology modeling, ecological modeling). Raw climate model projections also don't capture some important characteristics of observed weather and climate very well, such as statistics of daily precipitation.

Researchers have developed many different methods to translate raw climate model output into higher-resolution projections of local to regional climate changes. These *downscaling* procedures typically include a bias-correction step that aligns the raw climate model output to the observed mean and variance for each gridcell. These downscaled climate projections can be analyzed to assess local climate changes and used as inputs to hydrology models and other impact models.

As with CMIP5, most downscaled datasets produced from CMIP6 so far are *statistically* downscaled. Some *dynamically* downscaled datasets, which use finer-scale climate or weather models for downscaling over a regional domain, are becoming available. Note that data files for downscaled CMIP6 can be even larger than for the raw data, depending on the spatial domain and the resolution of the dataset. Downscaling also introduces additional modeling uncertainties, including differences in projected future climate due simply to the choice of downscaling method, and the choice of gridded observed climate dataset used in the bias correction and downscaling (see Figure 8.1).

Primary downscaled CMIP6 datasets

- **LOCA2** - North America (UC-San Diego/Scripps; Pierce et al. 2023)
  - *Update of the CMIP5 LOCA dataset; used in NCA5*
  - Daily data, statistically downscaled to 6-km (~4-mi.) grid, North America domain
  - SSPs (#models) SSP2-4.5 (24); SSP3-7.0 (23); SSP5-8.5 (22); one to ten runs per model-SSP pair
  - Variables[16]: T, P; 4 total
  - Easy to visualize with the USGS National Climate Change Viewer; limited download options through that portal
  - Download data: LOCA server and Globus service
    - Separate NetCDF file for each model-run-SSP-variable combination (~10 GB/ea); files of *monthly* averages (~600 MB/ea) and monthly averages spatially averaged over each U.S. county (~4 MB/ea) also available
    - LOCA server also has dataset split out by NCA region; file sizes are much smaller than for entire domain
    - *wget* script or equivalent desirable for downloading large sets of files from the LOCA server

- **NEX-GDDP-CMIP6** - Global (NASA; Thrasher et al. 2022)
  - *Update of the CMIP5 NEX-DCP30 dataset, uses BCSD[17] statistical downscaling*
  - Daily data, statistically downscaled to 25-km (~15 mi.) grid, Global domain
  - 35 models [no SSP breakdown], 1 run per model-SSP pair
  - Variables[16]: T, P, H, SR, W; six total
  - Download data: AWS S3; NCCS THREDDS
    - Separate NetCDF file for each model-run-SSP-variable-*year* combination (~200 MB/ea, so ~17 GB for full future period of 2015–2100 for one model)
    - *wget* script or equivalent desirable for downloading a large set of files

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[17] A variant of BCSD used in other downscaled CMIP3 and CMIP5 datasets has been found to produce a wet bias in precipitation over the western U.S. The particular implementation of BCSD in the NEX datasets does not produce this bias.

Other datasets/sources for downscaled CMIP6

- **CMIP6-WRF** - Western U.S. (UCLA; Rahimi et al. 2024)
  - *High-resolution dynamical downscaling using the Weather Research and Forecasting (WRF) model over western U.S. domains, focused on SSP3-7.0*
  - Daily and sub-daily data, dynamically downscaled to 9-km (~6 mi.) grid (W. U.S. domain) and 3-km (~2-mi.) grid (CA+NV domain)
  - SSPs (#models) SSP2-4.5 (1); SSP3-7.0 (17); SSP5-8.5 (1); one run per model-SSP pair
  - Variables[16]: T, P, H, Sn, Q, SM, SR, W; >30 total
  - Download data: AWS S3 (select "[model + SSP]_bc" and then "postprocess"); see also AWS registry
    - Separate NetCDF file for each model-SSP-run-variable-*year* combination (~16 MB/ea, so ~1.4 GB for full future period of 2015–2100 for one model)
    - *wget* script or equivalent desirable for downloading a large set of files

- **DOE ORNL SECURE (9505v3)** - CONUS (Oak Ridge National Laboratory; Kao et al. 2024a, 2024b)
  - *High-resolution statistical downscaling using DBCCA (Double bias-corrected constructed analogs) and dynamical downscaling (RegCMv4 model), plus corresponding hydroclimate and routed streamflow projections*
  - Daily data, downscaled to 0.04° (~4-km, ~2.5 mi.) grid
  - SSPs (#models): SSP1-2.6 (7) SSP2-4.5 (7); SSP3-7.0 (7); SSP5-8.5 (7); one run per model-SSP pair; dynamical downscaling only for SSP5-8.5 (6)
  - Variables[16]: T, P, H, Sn, Q, SM, ET, SR, LR, W; 18 total
  - Download data: ORNL Hydrosource server: Hydroclimate projections; Routed streamflow projections; those pages also have Globus links

- **ESPO-G6-R2** - N. America (Ouranos; Lavoie et al. 2024)
  - *High-resolution statistical downscaling using quantile mapping (similar to BCSD) primarily developed for Canada but includes the U.S.*
  - Daily and sub-daily data, dynamically downscaled to 0.09° (~9-km, ~6 mi.) grid
  - SSPs (#models) SSP2-4.5 (14); SSP3-7.0 (14); one run per model-SSP pair
  - Variables[16]: T, P; three total
  - Download data: Ouranos THREDDS server; several options for accessing/slicing data; output as netCDF files

- **BCCAQ** - Global (U. Southampton, UK; Gebrechorkos et al. 2023)
  - *Statistical downscaling using BCCAQ (Bias-corrected constructed analogs with quantile-map reordering), developed for climate impact analysis*
  - Daily data, statistically downscaled to 0.25° (~25-km, ~15 mi.) grid
  - SSPs (#models) SSP2-4.5 (18); SSP5-8.5 (18); SSP5-3.4-OS (6); one run per model-SSP pair
  - Variables[16]: T, P, W, H, PU; seven total

  - Download data: CEDA Archive (registration required)

- **GDPCIR** - Global (Climate Impacts Lab; Gergel et al. 2024)
  - *Statistical downscaling using Quantile Delta Mapping (QDM) combined with Quantile-Preserving Localized-Analog Downscaling (QPLAD) to better preserve extreme events*
  - Daily data, downscaled to 0.25° (~25-km, ~15 mi.) grid
  - SSPs (#models) SSP1-2.6 (20); SSP2-4.5 (23); SSP3-7.0 (20); SSP5-8.5 (22); one run per model-SSP pair
  - Variables[16]: T, P; three total
  - Download data: Microsoft Planetary Computer; see "example" tabs for Jupyter notebook (Python) instructions

Further reading:

- Vano and Lukas (2022). A User Guide to Climate Change Portals, Aspen Global Change Institute.

What do the identifiers for CMIP6 projections and files mean?

As with previous CMIPs, each individual model projection (i.e., one run of that model) has a unique identifier that is generally incorporated, in part or in full, into the name of the data files associated with that run/projection.

A complete identifier encodes nine different attributes of that run. When acquiring and compiling data for an analysis, one needs to be especially attentive to these three:

- The *model/version* that was run
- The *SSP/emissions scenario*
- The *realization* (run) number

For example, here is the complete identifier for one projection:

`CMIP6.ScenarioMIP.CCCma.CanESM5.ssp245.r3i1p1f1`

`CMIP6` For which *CMIP* the run was done

`ScenarioMIP` For which *activity* within CMIP6 that the run was done. It is very unlikely one would find runs from activities *other* than ScenarioMIP outside of the primary ESGF raw-data archive (see Q10)

`CCCma` The *modeling center* that built the model and performed the run (Canadian Centre for Climate Modelling and Analysis - Victoria, BC)

Note: The above three parts of the identifier may not always be incorporated into the file name, particularly in datasets of downscaled projections.

`CanESM5` The *model/version* that was run (Canadian Earth System Model, version 5)

`ssp245` The particular SSP or *emissions scenario* (SSP2-4.5) under which the model was run.

`r3` The *realization* (run) number. For the CMIP6 ScenarioMIP, the number of runs per model per emissions scenario can vary from 1 to 99. In this case, r3 is the 3rd run (of 50) from CanESM under SSP2-4.5, using slightly different initial conditions for each run. (To create an ensemble of climate projections in which each model is represented by a single run, it's convenient to use run 1, since an r1 will be available from all models[18]. There is no reason to believe that r1 is better or worse than any other run.)

`i1` The general type of *initialization* method used — the default (i1) was used in nearly all runs; very occasionally i2 was used, but this should not matter in using the data.

`p1` The *physics* configuration used in the run — most CMIP6 models were run using a single physics configuration (i.e., p1 for that model), but some were run using variants of model components, such as representation of clouds, to test the sensitivity of the output to those differences.

`f1` The specific *forcing* configuration used in the run — most typically f1, sometimes f2, or f3; this is used for internal tracking and not relevant to using the data.

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[18] For some models, some variables were not saved for run 1, but were saved for other runs.

Q11. What additional CMIP6 downscaling and modeling efforts are in progress? What new capabilities will they provide?

Short answer

As of Fall 2024, there are several CMIP6 downscaling efforts in progress that once completed will provide new capabilities: variables that are not available from other datasets, expanded visualization and data-handling options, and/or more physically realistic simulation of fine-scale processes and changes.

Long answer

Several CMIP6 downscaling efforts are in progress whose forthcoming data products may be useful to water utilities and other water interests in the U.S. The first three efforts listed here are U.S.-centered, and the developers are engaging with sectoral end users of the data (e.g., water resources, wildfire); CORDEX is global and more "research-oriented." This list is not intended to be comprehensive of all ongoing and planned CMIP6 downscaling efforts.

- **MACAv3 (CMIP6)** (UC-Merced Climatology Lab)
    - Forthcoming update to the widely used CMIP5-MACAv2 dataset
    - Will be accessible through the many Climate Toolbox visualization tools that currently show MACAv2 (CMIP5)
    - Will include many calculated variables (e.g., fire weather, agricultural weather, drought indices) not available in raw CMIP6 output or other CMIP6 downscaled datasets

- **CMIP6-LOCA2 Hydrologic Modeling** (NCAR, Reclamation)
    - Forthcoming update to the CMIP5-LOCA-VIC hydrology dataset currently available through GDO-DCP
    - SUMMA hydrologic modeling framework will be used
    - Data release will include some comparisons to VIC

- **ICAR** (Intermediate Complexity Atmospheric Model; Gutmann et al. 2016) **CMIP6** (NCAR)
    - "Hybrid" downscaling method that provides dynamical process simulation at much lower computational cost
    - Dataset will include downscaled output for five CMIP6 GCMs under three SSPs, for a Western U.S. domain

- **CORDEX** (Coordinated Regional Climate Downscaling Experiment) **CMIP6** (WCRP)
    - International research program that is gathering regional climate models (RCMs) for dynamical downscaling of global-model output
    - Currently 13 participating RCMs with grid of 25 km and/or 12.5 km

Q12. How can under-resourced communities and water providers best use CMIP6 (and/or CMIP5)? Are there specific resources that enable easier access to, and interpretation of, local or regional climate projections?

Short answer

When resources are limited, it may be more effective to use those resources to better understand a community's or water system's vulnerabilities and impact thresholds, rather than to perform new localized analyses of CMIP projections. Relevant climate change information can often be obtained "off-the-shelf," in climate assessments and similar resources. These resources include interpretation of the projected climate changes alongside curated graphics and key findings and messages.

Long answer

Below are several off-the-shelf resources:

- The two most recent National Climate Assessment reports (USGCRP 2018; USGCRP 2023a) have both U.S. maps of projected climate changes and separate regional chapters with region-specific maps and findings:
    - NCA4 (based on CMIP5)
        - National maps and findings: Ch. 2
        - Regional maps and findings: Ch. 18–27
    - NCA5 (based on CMIP6)
        - National maps and findings: Ch. 2
        - Regional maps and findings: Ch. 21–30

- The NOAA NCEI State Climate Summaries show state-specific graphics and results for all 50 states; they were last updated in 2022 and show CMIP5-based projections.

- Individual climate assessments have also been developed for 25 states, for many cities, and for several other regions in the U.S. In some cases, the assessment has associated web tools or portals. To find these resources, first go to CAKE (Climate Adaptation Knowledge Exchange) and enter the state into the search bar. CAKE may not have the most recently completed assessments, so also do a general web search.

If the resources above don't provide the level of information needed, then:

- The U.S. EPA Climate Resilient Water Utilities (CRWU) program developed the Climate Resilience Evaluation & Awareness Tool (CREAT) to assist water sector utilities in assessing climate-related risks to utility assets and operations. The tool provides users access to locally relevant CMIP5 datasets (but limited variables) and walks the user through modules to consider climate impacts and identify adaptation options to increase resilience. To accompany the tool, EPA developed the CREAT Climate Scenarios Projection Map to provide easy-to-access, scenario-based climate change projections without having to go through the CREAT modules. The CREAT team is currently updating the climate model datasets loaded in the tool.

- The USGS National Climate Change Viewer provides reasonably user-friendly visualization of downscaled, projected climate at the local (county) level for both CMIP6 (LOCA2) and CMIP5 (MACAv2), and downloading of monthly summary data (ensemble mean) and monthly data from individual models, for 24 different variables, from 1950–2100.

- The AGCI User Guide to Climate Portals has additional links, direction, and guidance for accessing and using climate-change information from web portals and other sources. While this guide mostly focuses on navigating climate change data, it also recognizes that is only part of what is needed to inform a climate adaptation process, and so it briefly covers Adaptation Guidance and Climate Service Providers.

Further reading:

- Vano and Lukas (2022). A User Guide to Climate Change Portals, Aspen Global Change Institute.

Q13. What studies have already been conducted using CMIP6 by or on behalf of water agencies? What was learned about CMIP6?

Short answer

As of Fall 2024, a handful of research and assessment efforts using CMIP6 have been conducted by or on behalf of water agencies in Oregon, Colorado, and Florida. More studies will be coming out soon.

Long answer

Below are short overviews of the studies and assessments to date and their key findings.

CMIP6 model performance over the Pacific Northwest (Taylor et al. 2023; Portland Water Bureau)
Supported in part by Portland Water Bureau, Taylor et al. (2023) analyzed the raw output of 25 CMIP6 models to evaluate their fidelity in simulating several common, large-scale atmospheric circulation patterns (e.g., low- and high-pressure systems) that drive seasonal precipitation anomalies in the Pacific Northwest. They found that the CMIP6 models are generally able to simulate the range of observed circulation patterns with reasonable fidelity, although model skill varies across the ensemble. This generates confidence that the models, when simulating regional precipitation and temperature anomalies, do so for the correct physical reasons. They did not, however, compare the CMIP6 models' performance with CMIP5 models.

Climate Change in Colorado (Bolinger et al. 2024; Colorado Water Conservation Board)
The 3rd edition of the Climate Change in Colorado report (Bolinger et al. 2024), produced in partnership with the Colorado Water Conservation Board, compared raw CMIP5 (36 models) and CMIP6 (37 models) projections of statewide-average change in annual temperature and annual precipitation, under 4.5 emissions scenarios. The results of this Colorado-focused comparison were consistent with results of the CONUS-wide and regional comparisons described in Q7:

- The CMIP6 ensemble range was overall shifted warmer (Figure 13.1) and slightly wetter relative to CMIP5, with substantial overlap between the ensemble ranges.
- Screening out CMIP6 hot models (using Likely TCR) reduced the warming gap between CMIP6 and CMIP5 by ~50%, but had no effect on the CMIP6 precipitation change.
- After screening, CMIP6 was still slightly warmer and slightly wetter than CMIP5 for Colorado, so modeled hydrologic outcomes using screened CMIP6 will likely have a very similar range and mean as using CMIP5.

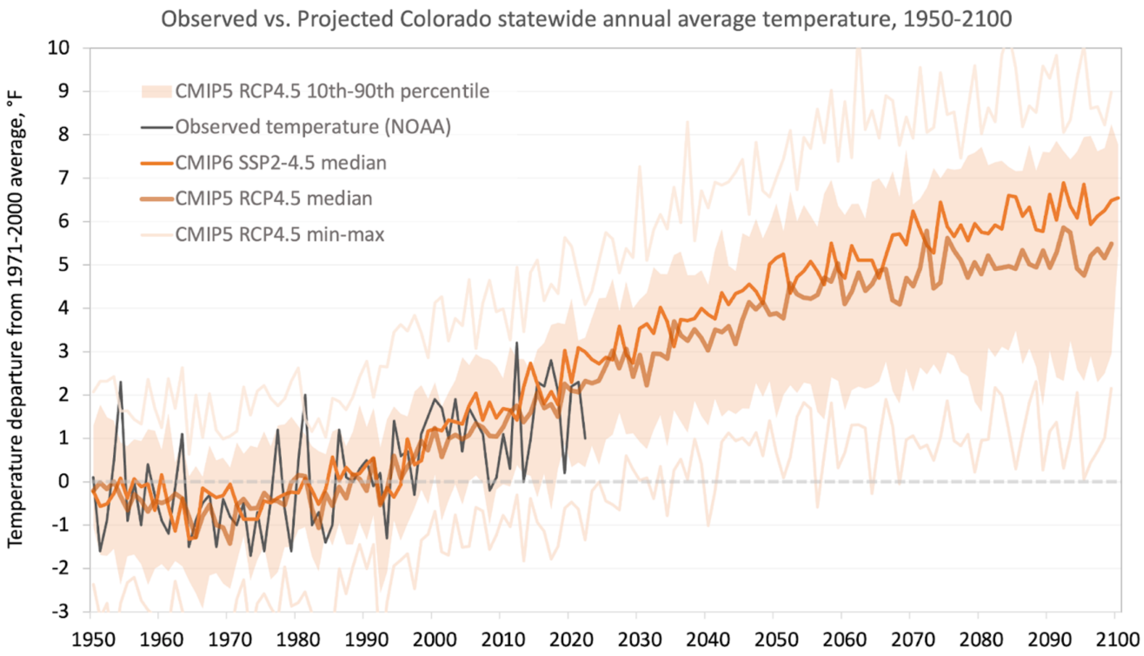

Figure 13.1. Projected change in Colorado statewide average annual temperatures to 2100, relative to a 1971–2000 baseline, from raw CMIP5 model output (median and range) and raw, unscreened CMIP6 model output (median only) under medium-low emissions scenarios (RCP4.5, SSP2-4.5), compared to observed temperatures through 2022. The median warming seen in CMIP6 diverges from the CMIP5 median after 2020, with the difference increasing to ~1.0°F by 2070. (Figure 2.7 in Bolinger et al. 2024)

CMIP6 vs. CMIP5 model performance: Florida precipitation (Wang and Asefa 2024; Tampa Bay Water)
Wang and Asefa (both with Tampa Bay Water) assessed the performance of 18 CMIP5 and 27 CMIP6 models in simulating historical monthly precipitation for 24 grid boxes across Florida. They found that the CMIP6 models, overall, were significantly better than the CMI5 models in terms of bias (too much/too little) in simulated monthly average precipitation, simulation of the seasonal cycle of precipitation, and simulation of the onset and end of the summer rainy season. Spatially, in both CMIP6 and CMIP5, precipitation over the Peninsula was better simulated than precipitation over the Panhandle.

Further reading:

- Taylor et al. (2023). CMIP6 model fidelity at simulating large-scale atmospheric circulation patterns and associated temperature and precipitation over the Pacific Northwest.
- Bolinger et al. (2024). Climate Change in Colorado. 3rd edition.
- Wang and Asefa. (2024). Enhanced performance of CMIP6 climate models in simulating historical precipitation in the Florida Peninsula.

Glossary

For a much more comprehensive glossary of climate-related terms, see the IPCC AR6 WG1 (2021) Glossary.

Climate model – A complex math- and computer-based simulator of the climate system (atmosphere, oceans, ice sheets, land surface), which uses both fundamental physical laws and observed relationships to model the evolution of climate over time and space. Climate models that also include biogeochemical cycling (e.g., carbon cycle) are also referred to as **Earth system models**, or ESMs.

Downscaling – A procedure by which the data from a global climate model (see **GCM**) projection is translated to finer spatial resolution to make it more usable for local and regional analysis and decision-making. LOCA, MACA, BCSD, and BCCA are examples of different types of downscaling procedures and their associated datasets.

Earth system model (ESM) – See **Climate model**

Emissions scenario – A potential trajectory of greenhouse gas emissions and concentrations over the next century given particular societal choices; a simulation (projection) of the future by a climate model is driven by a particular emissions scenario (see **RCP**, **SSP**).

Equilibrium climate sensitivity (ECS) – Refers to the equilibrium (steady-state) change in the annual global mean surface temperature, in °C, following a doubling of the atmospheric carbon dioxide (CO_2) concentration.

Ensemble – A group of model simulations of historical or future climate conditions. Most commonly this refers to multi-model ensembles (e.g., from CMIP6) with one or more simulations made by each of several models. The spread of results across a multi-model ensemble can provide an estimate of model uncertainty. Ensembles can also be made with one model using different initial conditions; such single-model ensembles can characterize the uncertainty associated with natural (internal) climate variability.

Forcing – An external driver of the climate system; for example, a change in the concentration of CO_2 or change in radiation from the sun; can also refer to the net effect of all external drivers, such as in the RCPs and SSPs (e.g., 4.5 W/m^2 at 2100).

Global climate model (GCM) – See **Climate model**

Greenhouse gases (GHGs) – Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This absorption and emission of energy causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary GHGs in the Earth's atmosphere. There are also many entirely human-made GHGs in the atmosphere, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and other chlorine- and bromine-containing substances. (IPCC 2021).

Initialization – The specification of the initial conditions at the beginning of climate model simulation. In a weather model forecast, the model's initial conditions are derived from observations. For climate models, the initial conditions for future projections come from time-slices chosen from control runs or from the end of historical simulations.

Parameter – A quantitative term in a climate model, derived from observations or other modeling, used to represent a process that cannot be explicitly resolved at the spatial or temporal resolution of the model (i.e., subgrid-scale processes) using the model's physical equations.

Projection – One simulation of future climate from a single GCM, which assumes a particular future emissions scenario. Because the simulation is conditional on that scenario, technically it's not a *prediction* or a *forecast*.

Representative Concentration Pathway (RCP) – One of a set of emissions scenarios associated with a specified "climate forcing" (excess energy retained in the Earth system), used to drive the simulations from CMIP5 climate models.

Run – See **Projection.**

Shared Socioeconomic Pathway (SSP) – A broad scenario of future population, policy, economic growth, and technology, that in conjunction with a specific emissions trajectory (see **RCP**) was used to drive the simulations from CMIP6 climate models.

Transient climate response (TCR) – The change in the global mean surface temperature, in °C, averaged over a 20-year period, centered at the time of atmospheric CO_2 doubling, in a climate model simulation in which CO_2 increases at 1%/year from pre-industrial conditions. It is a measure of the strength of climate feedbacks and the timescale of ocean heat uptake. TCR is the shorter-term equivalent of **Equilibrium Climate Sensitivity (ECS)**.

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