Climate Adaptation Partnership

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Climate modeling:
an introductory primer for practitioners

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Climate modeling: an introductory primer for practitioners

About this document

This document is intended to provide an introductory overview to climate models and their function. It explains the basics of how a climate model works, how data can be transformed from a global to a regional scale, and the constraints placed on modeling as a result of computational power. It also explains the Coupled Model Intercomparison Project (CMIP) and modeling scenarios established by CMIP. It is not an exhaustive overview, nor is it intended to replace a formal modeling course for those wishing to run climate models. The intended audience includes those who would like to understand or are interested in using model output.

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www.climate.umn.edu/climate-projections

Contact Us

climate.umn.edu
mnclimate@umn.edu

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Climate model basics

What are climate data?


Photo: UMN Extension, 2023

Climate data describe the long-term averages of a region's climate based on characteristics such as precipitation, temperature, humidity, and more. The main difference between climate data and weather data is time. Weather refers to the daily measure of temperature, rainfall, wind, etc., while climate refers to an average of these values over a much longer time period, usually around 30 years or more.

For example, while climate tells us that February in Minnesota is typically cold, weather describes the temperature on a particular day. While we may endure a snowstorm in April, this is not evidence that global warming is not occurring, because a snowstorm is a weather event - not climate. These variations in our weather have occurred and will always occur. Climate change describes a change in the long-term average, which can also make these extreme events even more extreme.

Climate models provide us a view into potential changes in Earth's climate through a range of data representing projections of temperature, precipitation, wind speed, and other important climate characteristics.

What are the types of climate data?

There are two basic types of climate data: historical and projected.

Historical climate data are calculated from observations taken over many years. For centuries, people have collected and used historical climate data to inform crop planting, infrastructure planning, and water management. Around the world, millions of observations are recorded daily by both human observers and automated weather stations. When daily weather data for a location or region are compiled and averaged over multiple decades, they represent the climate for that area.

Climate projections are simulations of what the climate may look like in the future. Models allow us to simulate Earth's climate in order to understand how various systems behave and interact, particularly when altered by greenhouse gas emissions.

What are climate models?

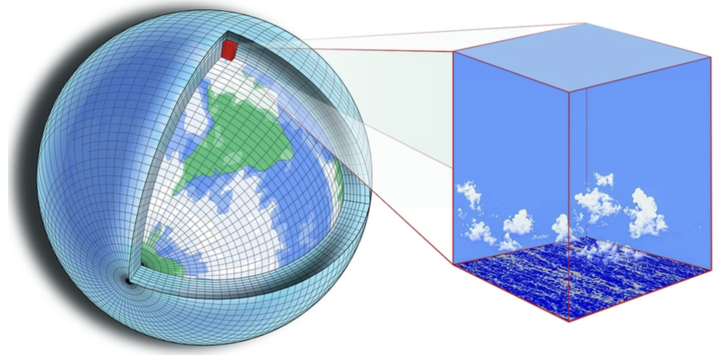

Image: Caltech and Tapio Schneider, 2018

Climate models are computer programs that simulate the various processes that interact to create the Earth's climate. Climate models can represent the past if they use observed data, or they can represent the future. Models built to represent potential climate futures calculate projections of important climate characteristics, like temperature and precipitation. They are the best tool scientists have to predict how the Earth's climate may change. Climate modeling has existed for decades, but recent advances in computer technology have fueled rapid improvements in model output.

> One of the first computer simulations to project the future climate was by scientists in the 1970s to see what happened when carbon dioxide concentrations doubled in the atmosphere. Results showed that the planet warmed by about 2.5 degrees Celsius (almost 5 degrees Fahrenheit) after a doubling of CO_2 concentrations, a value which is still consistent with today's best estimates.

How do climate models work?

Climate models separate the earth and its atmosphere into 3-dimensional boxes called grid cells. These cells cover the earth's surface and extend up into the atmosphere. The size of the grid cells determines a model's ***spatial resolution*** - smaller grid cells produce higher resolution. Depending on the model, there can be hundreds of thousands - or even millions - of grid cells!

Within each cell are numerous mathematical equations representing the physics, chemistry and biology of the atmosphere, land, water and ice within and around that cell. Results from one cell are passed to the neighboring cell to model the exchange of matter and energy over time over the entire surface of the earth and up into the atmosphere.

Climate models calculate climate characteristics across space and time. To do this, models have to break time into discrete chunks - known as time steps. The size of the time step determines a model's ***temporal resolution*** - shorter time steps have a higher resolution. The model calculates the equations at the first time step, then uses that information to predict how things will look at the next step. It's similar to driving a car and estimating where you will be 5 minutes in the future based on where you are, what direction you're facing, and how fast you're moving. Because each equation is calculated in each cell at each time step, a single model run solves millions of equations, requiring use of the largest, fastest supercomputers in the world.

Learn more about climate models and topics like computational capacity and downscaling.
For a full list of references, please refer to the end of the packet.

What is downscaling?

Local level climate information

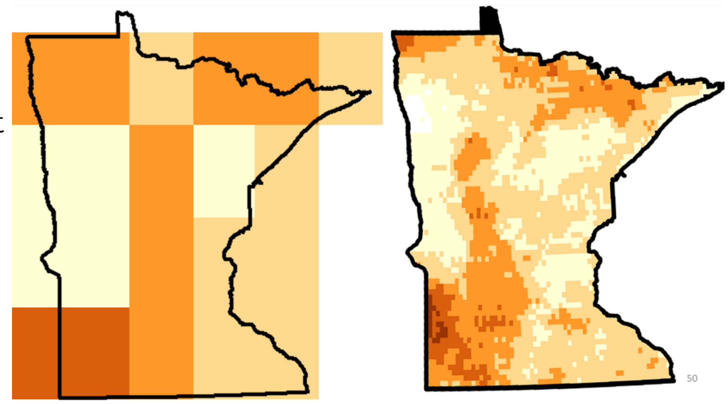

Image: Public domain

The amount of detail across time and space that a climate model can represent is determined by its ***resolution***. In order to model a process, the spatial resolution must be fine enough and the temporal resolution must be short enough to capture that process, whether it's quick forming clouds over your city or a long drought over the entire Midwest region.

The term downscaling refers to a process modelers use to increase the resolution of a global climate model (GCM) in order to simulate climate change at smaller scales. Information at a more local level, such as regional or city scales, is more relevant and usable for adaptation planning.

Scientists use **downscaling** to increase the detail captured by the climate models they develop. There are two types of downscaling: **statistical and dynamical.**

Statistical downscaling compares output from a GCM for a certain time in the past, like estimates of temperature, with local observations from that same time period. By comparing output from the GCM with actual climate measurements, scientists can identify patterns or relationships between the GCM and local climate phenomena and describe these relationships using statistics.

A key aspect of statistical downscaling is that it assumes that these relationships observed in the past will remain constant into the future, a concept called stationarity.

For example, let's say that a scientist builds a GCM and runs the model for a historical time period, such as 1990-2010. The GCM output calculates that for Region X, annual average temperature was 60 degrees Fahrenheit (˚F). Fortunately, that modeler also has access to past observations from weather stations all over Region X. These data suggest that the annual average temperature during 1990-2010 was closer to 62˚F. Statistically speaking, the GCM output for Region X equals the annual average temperature plus 2˚F. In this example, adding 2˚F helps correct the GCM output using feedback from local data. A simple approach to statistically downscaling the GCM for Region X in this example would mean adding 2˚F to the annual average temperature that the model projects for time periods in the future.

The other main approach to downscaling, **dynamical downscaling**, uses the output from a GCM to create the initial conditions and boundaries of a higher resolution Regional Climate Model (RCM).

In other words, in place of observed data, modeled output is used to tell the RCM what is happening at the beginning (initial conditions) and at the edges (boundary conditions) of the model. Information from the GCM is fed to the RCM at each time step in the simulation.

Dynamical downscaling requires a lot more computing power. However, it avoids the problem of stationarity, which assumes that the mathematical relationship between a GCM and observed data will remain the same moving into the future. Instead, it works to model the physical processes underlying or creating these relationships, respecting that these relationships are "dynamic," depending on many internal and external factors that can change over time. Because the results are physical, a climate modeler can model extremes, such as extreme heat days, and it requires fewer historical observations than statistical downscaling. Unfortunately, as dynamical downscaling is computationally "expensive," this limits the number of GCMs that can be downscaled, and it necessitates the use of supercomputers, like those at the Minnesota Supercomputing Institute.

"Initial conditions" and "boundary conditions" are the terms that climate modelers use to describe the information that is fed into the model: they are values for temperature, wind speed, rainfall, etc., that tell the model what is happening in the system either at the beginning of the model run (initial conditions), or outside the model grid (boundary conditions).

Which technique is better?

Both statistical and dynamical downscaling serve a purpose, and neither is explicitly better than the other: it depends on the computing capacity that is available and the specific project needs or management question..

Statistical downscaling requires less computing capacity, so modeling often can be performed using the power of a single computer and results arrive quicker. Less demand for computing power also means that more GCMs can be downscaled. It might be the appropriate choice if you don't have access to a supercomputer, if you have an extensive observational dataset, if you want results quickly, or if you aren't as concerned with the physical processes underlying the data.

However, even though it requires the use of supercomputers, dynamical downscaling has advantages as well. This method allows the developer to explore how specific physical processes might change in the future or the occurrence of extremes. It can also be used to test how sensitive the system is to a change in one particular value (e.g., air temperature).

For a full list of references, please refer to the end of the packet.

Computational and storage capacity

Balancing resolution and computing power

There is a tradeoff between a climate model's resolution (in both time and space) and the time and computing power required to run it. A model may contain thousands to millions of grid cells, each containing dozens of equations. Running the model means powering through hundreds of thousands of equations for each individual time step.

A century-long climate simulation with a 30-minute time step would require 1,753,152 time steps (the number of half-hours in a century), so one single climate simulation would require solving trillions of equations!

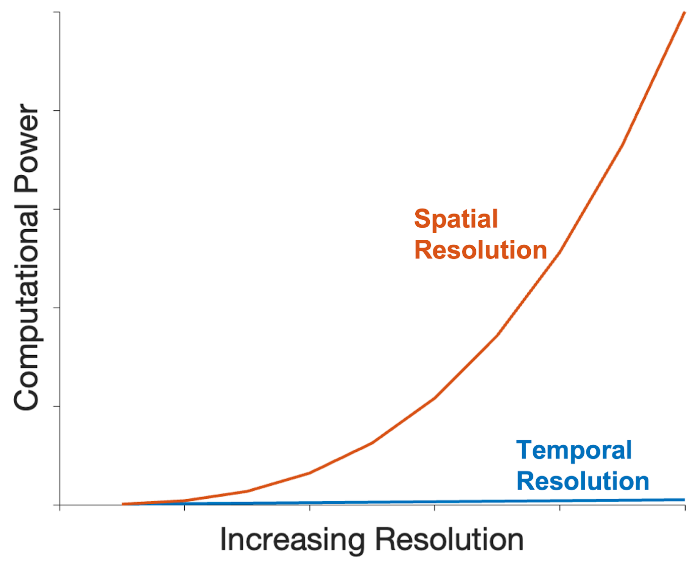

Image: University of Minnesota Climate Adaptation Partnership, 2023

Increasing a model's temporal resolution by a factor of two (simulating information at 30 minute increments instead of 60 minutes, for example), increases the total time steps by a factor of two. Spatial resolution is a bit more complex. Because space is three dimensional, increasing the spatial resolution in each dimension by a factor of two increases the number of equations to calculate at each time step by eight (2x2x2=8).

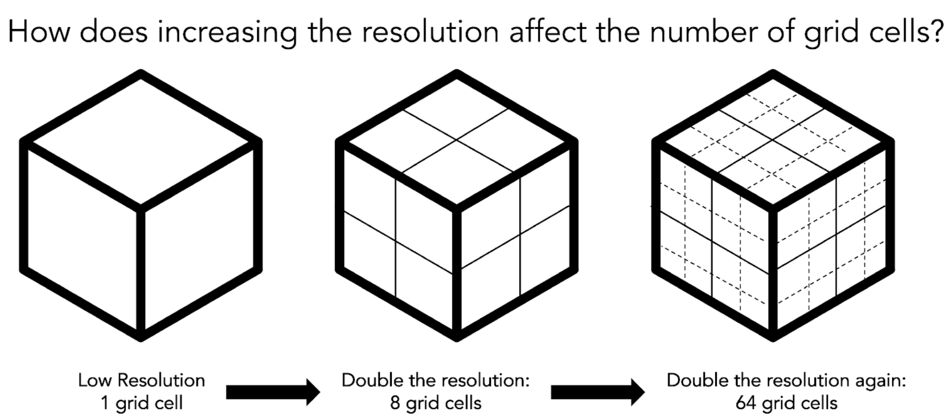

Image: University of Minnesota Climate Adaptation Partnership, 2023

Typically, smaller processes happen faster. Cloud formation is a relatively small and fast process, while ocean currents are large and slow. Since the first Intergovernmental Panel on Climate Change (IPCC) report in 1990, global climate model resolution has improved from 500km (310 miles) on the land surface to 100 km (60 miles). This is because computers have gotten faster and more powerful.

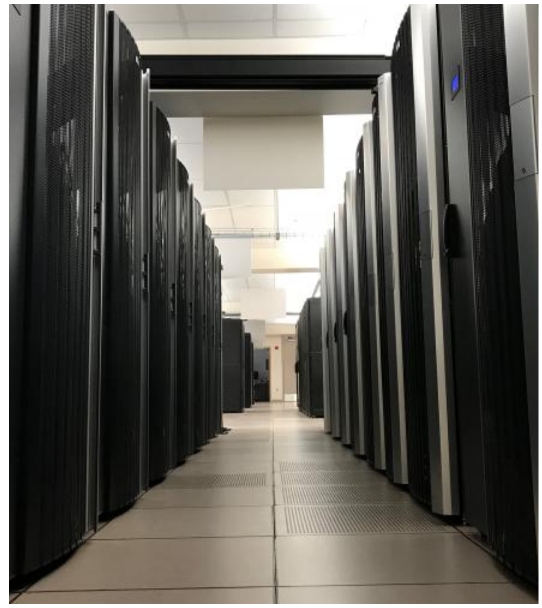

Image: The Supercomputer at MSI (UMN Extension, 2023)

The computers required to run climate simulations are giant; they can fill a room the size of a tennis court. Most academic institutions don't have their own supercomputers, so they pay to use one somewhere else, such as at the National Center for Atmospheric Research. The University of Minnesota is fortunate to have its own supercomputers at the Minnesota Supercomputing Institute (MSI). In fact, the UMN was the first U.S. university to acquire a supercomputer back in 1981.

University of Minnesota Climate Adaptation Partnership climate modelers benefit from the extensive computing power and storage capacity available at the world-class Minnesota Supercomputing Institute.

Storage capacity

Computational capacity determines what we can simulate. Storage capacity determines what we can save. A single 20-year climate simulation generates about 30 terabytes of data. Compare that to an iPhone 13 with about 256 gigabytes of storage. It would take approximately 120 iPhones to store all of the output from one climate simulation, and we often run dozens of simulations for different time periods and global climate models!

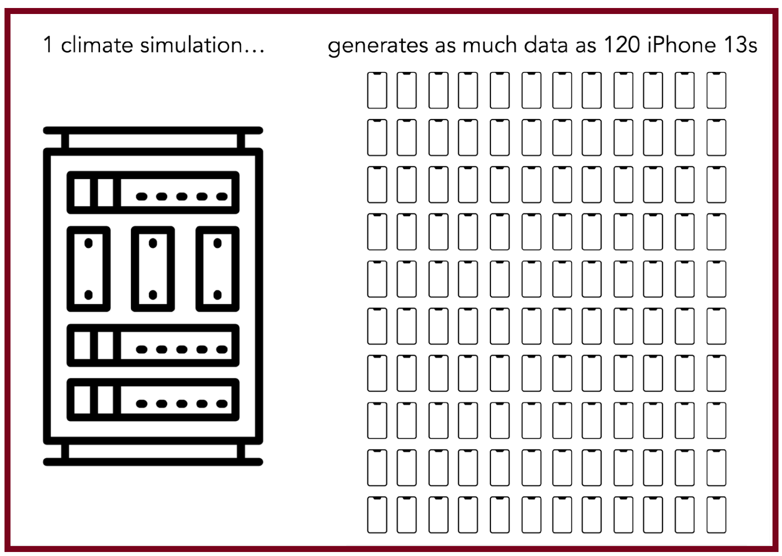

Image: University of Minnesota Climate Adaptation Partnership, 2023

Typically, scientists reduce the amount of storage needed by only saving a fraction of the simulated time steps. A model might be run with a time step of one hour, for example, but the data might only be saved for every 6 hours. The results from each grid cell are averaged over 6 hours before saving.

For a full list of references, please refer to the end of the packet.

About CMIP

Coupled Model Intercomparison Project

The Coupled Model Intercomparison Project (CMIP) is an international effort to simulate changes to the earth's systems - the geosphere, biosphere, cryosphere, hydrosphere, and atmosphere - with computer models. CMIP is not one single model, but a collective project consisting of dozens of models developed and run by scientists all over the world. It facilitates cooperative research between modeling teams so that their model results inform and benefit the work of all the others.

Figure: Flag circles represent climate modeling groups contributing to the Coupled Model Intercomparison Project. Map by CMIP6.

CMIP establishes a set of standard simulations that each team runs through their model. This allows results to be directly comparable across different models, to see where models agree and disagree on future changes, and to make our predictions more robust. One of the project's primary goals is to deliver model output in a standardized format.

> Like the International Space Station, CMIP is a powerful example of experts across nations transcending geopolitical boundaries to advance the limits of science and technology.

Why do we need to coordinate these different modeling efforts?

Global Climate Models (GCMs) models vary in their construction: while all of them model the earth as a whole, they focus on different phenomena (such as tropical monsoons vs. polar sea ice), use different grids, or make different approximations to estimate small-scale processes.

CMIP Goals

- Understand past, present, and future climate changes that arise from either natural or human emissions.
- Assess model performance for historical periods to determine how well the model predicts future climates.
- Make projections based on climate data we have already observed.

CMIP6

Since 1995 when CMIP was created, it has coordinated five large model intercomparison projects to fuel the evolution of climate modeling. As of the publication of this document, results from the sixth CMIP (CMIP6) have just been released and represent a major expansion in terms of the number of modeling groups participating and the number of future scenarios examined. Some modeling groups have improved their representation of physical processes, and many have increased their spatial resolution. The biggest difference, however, between CMIP5 and CMIP6 is the formulation of future scenarios. For more on climate model scenarios, see Scenarios: RCPs vs SSPs.

For a full list of references, please refer to the end of the packet.

Scenarios: RCPs vs. SSPs

The concept of scenarios is very important in the development, interpretation and application of future climate projections. Since we can't know for sure what the future holds, each model is run with a variety of scenarios to simulate a range of potential outcomes. The largest source of uncertainty when projecting the future global climate comes from not knowing at what rate global society will continue to emit greenhouse gasses.

Representative Concentration Pathways (RCPs)

The 5th Coupled Model Intercomparison Project (CMIP5) used scenarios called Representative Concentration Pathways (RCPs), which are based on the amount of radiative forcing at the earth's surface. The scenarios ranged from RCP2.6, which requires an immediate reduction in CO_2 emissions and would lead to an estimated warming of 1.8 degrees Celsius (˚C) (3.2˚ degrees Fahrenheit) by 2100, to RCP8.5, a high-end scenario, which would lead to an estimated warming of 4.3˚C (7.7˚F) by 2100.

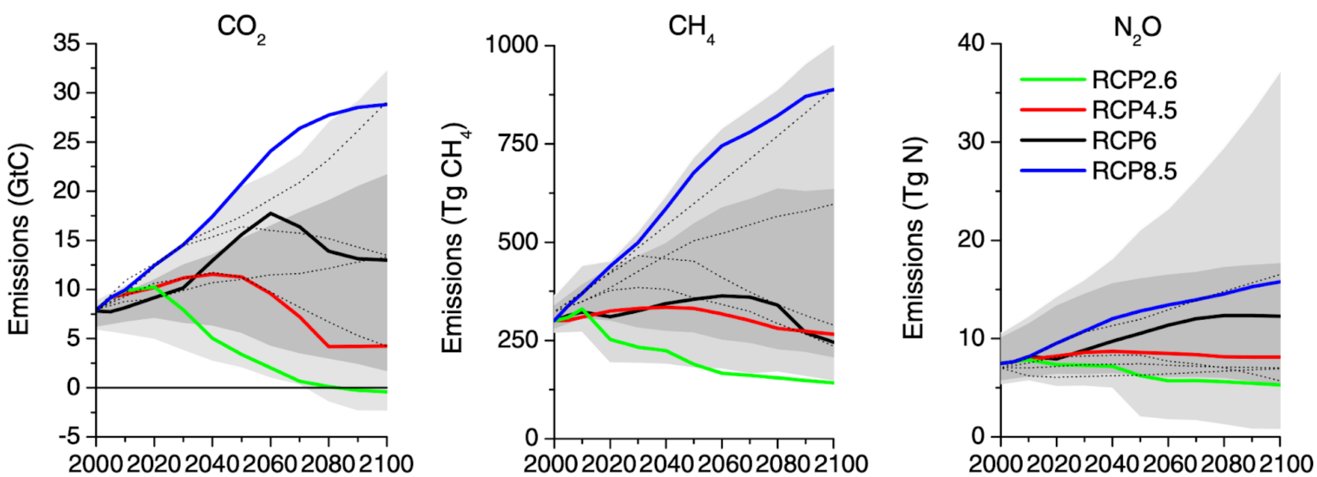

Image: van Vuuren et al., 2011

RCP8.5 has been misrepresented as a "worst-case" scenario, when in fact it is one example of a very high emissions scenario that could result from a no-climate policy world. For example, the carbon emissions represented in RCP8.5 would require a significant return to coal-powered energy, something that is not likely given the energy transition already underway to cleaner sources, like wind, solar and electric.

Shared Socioeconomic Pathways (SSPs)

To account for social and economic decisions that will significantly impact future emissions scenarios, CMIP6 uses Shared Socioeconomic Pathways, or SSPs. The SSPs reflect assumptions about how industrialization, fossil fuel dependence, land use, and population density, evolve in the future. The assumptions are based on population growth, urbanization, economic growth, technological advances, greenhouse gas and aerosol emissions, energy supply and demand, land-use changes, and more.

SSP1 - Sustainability: the world shifts toward sustainable development, low material consumption, greater equality, and more renewable energy.

SSP2 - Middle of the Road: economic, social and technological trends follow historical patterns. Population growth is moderate and inequalities persist.

SSP3 - Regional Rivalry: resurgent nationalism causes countries to focus on regional issues of security, at the expense of cross-border collaboration and development.

SSP4 - Inequality: unequal investments increase the inequality between a highly connected, knowledge- and capital-investment sector of society and a less-educated, lower-income, labor-based society.

SSP5 - Fossil-fueled development: There is rapid development in competitive markets and investments in health, education and human capital, driven by increased fossil fuel consumption.

SSPs vs. RCPs

These two types of scenarios are complementary. RCPs describe the physical process - greenhouse gasses emissions - and SSPs describe the social process - how our behavior will contribute to these emissions. It's important to understand that not all RCP scenarios are achievable under all SSP scenarios. SSP3, for example, the "Regional Rivalry," assumes that countries do not work together to develop sustainably and makes lower emissions scenarios nearly impossible. In contrast, SSP1, "Sustainability," focuses on renewable energy and equitable solutions, enabling a variety of RCP emissions scenarios. The SSPs emphasize a critical point – **we as a society still have a choice as to what our future holds.**

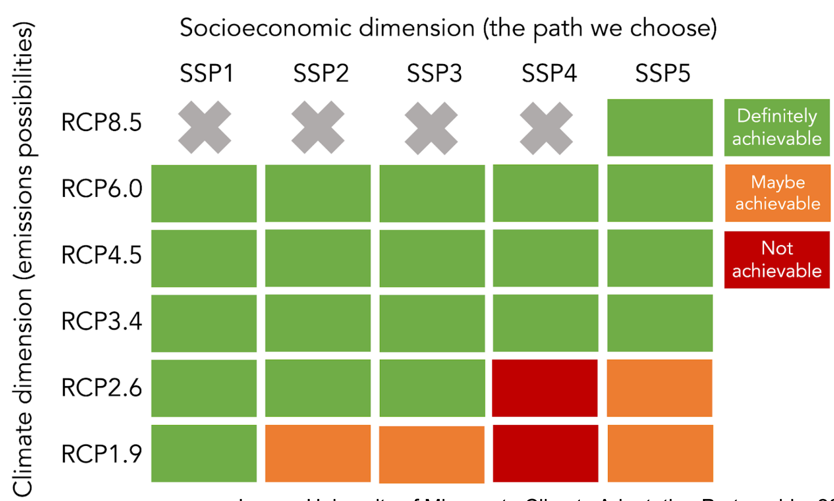

Image: University of Minnesota Climate Adaptation Partnership, 2023

For a full list of references, please refer to the end of the packet.

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