What's the difference between climate and weather models? It all comes down to chaos

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Weather forecasts help you decide whether to go for a picnic, hang out your washing or ride your bike to work. They also provide warnings for extreme events, and predictions to optimise our power grid.

To achieve this, services such as the Australian Bureau of Meteorology use complex mathematical representations of Earth and its atmosphere – weather and climate models.

The same software is also used by scientists to predict our future climate in the coming decades or even centuries. These predictions allow us to plan for, or avoid, the impacts of future climate change.

Weather and climate models are highly complex. The Australian Community Climate and Earth System Simulator, for example, is comprised of millions of lines of computer code.

Without climate and weather models we would be flying blind, both for short-term weather events and for our long-term future. But how do they work – and how are they different?

The same physical principles

Weather is the short-term behaviour of the atmosphere – the temperature on a given day, the wind, whether it's raining and how much. Climate is about long-term statistics of weather events – the typical temperature in summer, or how often thunderstorms or floods happen each decade.

The reason we can use the same modelling tools for both weather and climate is because they are both based on the same physical principles.

These models compile a range of factors – the Sun's radiation, air and water flow, land surface, clouds – into mathematical equations. These equations are solved on a bunch of tiny three-dimensional grid boxes and pieced together to predict the future state.

These boxes are sort of like pixels that come together to make the big picture.

These solutions are calculated on a computer – where using more grid boxes (finer resolution) gives better answers, but takes more computing resources. This is why the best predictions need a supercomputer, such as the National Computational Infrastructure's Gadi, located in Canberra.

Because weather and climate are governed by the same physical processes, we can use the same software to predict the behaviour of both.

But there most of the similarities end.

The starting point

The main differences between weather and climate come down to a single concept: "initialisation", or the starting point of a model.

In many cases, the simplest prediction for tomorrow's weather is the "persistence" forecast: tomorrow's weather will be similar to today. It means that, irrespective of how good your model is, if you start from the wrong conditions for today, you have no hope of predicting tomorrow.

Persistence forecasts are often quite good for temperature, but they're less effective for other aspects of weather such as rainfall or wind. Since these are often the most important aspects of weather to predict, meteorologists need more sophisticated methods.

So, weather models use complex mathematics to create models that include weather information (from yesterday and today) and then make a good prediction of tomorrow. These predictions are a big improvement on persistence forecasts, but they won't be perfect.

In addition, the further ahead you try to predict, the more information you forget about the initial state and the worse your forecast performs. So you need to regularly update and rerun (or, to use modelling parlance, "initialise") the model to get the best prediction.

Weather services today can reliably predict three to seven days ahead, depending on the region, the season and the type of weather systems involved.

Chaos reigns

If we can only accurately predict weather systems about a week ahead before chaos takes over, climate models have no hope of predicting a specific storm next century.

Instead, climate models use a completely different philosophy. They aim to produce the right type and frequency of weather events, but not a specific forecast of the actual weather.

The cumulative effect of these weather events produces the climate state. This includes factors such as the average temperature and the likelihood of extreme weather events.

So, a climate model doesn't give us an answer based on weather information from yesterday or today – it is run for centuries to produce its own equilibrium for a simulated Earth.

Because it is run for so long, a climate (also known as Earth system) model will need to account for additional, longer-term processes not factored into weather models, such as ocean circulation, the cryosphere (the frozen portions of the planet), the natural carbon cycle and carbon emissions from human activities.

The additional complexity of these extra processes, combined with the need for century-long simulations, means these models use a lot of computing power. Constraints on computing means that we often include fewer grid boxes (that is, lower resolution) in climate models than weather models.

A machine learning revolution?

Is there a faster way?

Enormous strides have been made in the past couple of years to predict the weather with machine learning. In fact, machine learning-based models can now outperform physics-based models.

But these models need to be trained. And right now, we have insufficient weather observations to train them. This means their training still needs to be supplemented by the output of traditional models.

And despite some encouraging recent attempts, it's not clear that machine learning models will be able to simulate future climate change. The reason again comes down to training – in particular, global warming will shift the climate system to a different state for which we have no observational data whatsoever to train or verify a predictive machine learning model.

Now more than ever, climate and weather models are crucial digital infrastructure. They are powerful tools for decision makers, as well as research scientists. They provide essential support for agriculture, resource management and disaster response, so understanding how they work is vital.