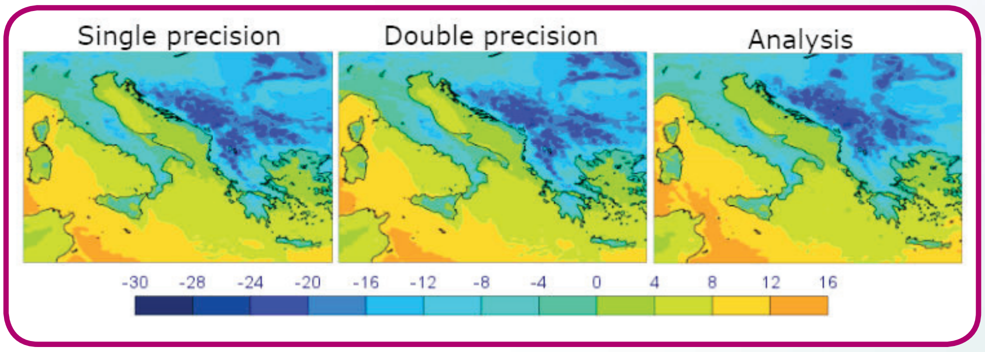
MATHEMATICS
**MATTERS**

# Calculating the weather: Using mathematics to improve weather prediction




The impact of weather prediction cannot be underestimated. Accurate weather forecasting not only helps save lives by helping people prepare for extreme weather events, it is also vital to the economy, for example by helping farmers to decide on when to harvest a crop, or by impacting decisions on how much seasonal stock a business should produce. Weather forecasting has been steadily improving over the last 40 years, as a result of both better computing power and advanced mathematical techniques. For example, 20 years ago a three-day forecast was only as accurate as a five-day forecast is today.

Weather forecasting is heavily reliant on supercomputers which are used to solve the mathematical equations that describe the weather. One of the reasons that there has been such a steady improvement in weather forecasting is that computing power has also been constantly improving. In the 1960s Gordon Moore, a co-founder of Intel made a prediction that computing power would double approximately every two years, based on the idea that the components on computer chips would be made smaller and smaller to allow faster computations.

There is however a catch to what is now known as 'Moore's Law' – components can't keep getting smaller indefinitely – and Moore's Law will inevitably fail at some point in the future. In fact, the slow-down of Moore's Law has already started to be seen in practice. The result is that individual components of supercomputers will not become much faster in the future. Further improvements to the speed of supercomputers will require costly increases in the physical size of the computers as well as a significant rise in power consumption. There are huge costs associated with the electricity needed to run a supercomputer – amounting to a multi-million pound annual bill. Therefore, improvements in weather prediction will need to come mainly from developments in mathematics rather than raw improvements in computing power and there is a strong incentive to reduce or maintain the computing power needed, while still improving the accuracy of the forecast.

Researchers at the European Centre for Medium-Range Weather Forecasts (ECMWF) have been developing a novel approach which is designed to reduce the computing power needed for forecasting. When a weather forecast is made, a number of physical quantities, such as wind speed need to be represented in the mathematical model, which then predicts what the weather will be like in the future. At the moment these quantities are represented with a high degree of accuracy. In computer language they are stored at a precision of '64 bits' – in common language, this translates into a number which is accurate to about 15 decimal places. The researchers at ECMWF have explored whether 64 bit precision is actually needed, and have made forecasts using initial measurements which are only '32 bit' precision, meaning that they are only correct to 7 decimal places. They have found that this has produced a forecast which is the same quality, but which is produced 40% faster.

In reality the desire for more accurate weather forecasts will mean that the 40% time saving will allow forecasters to make other improvements such as increasing the complexity of the mathematical model, increasing the forecast range or increasing the resolution of the forecast.

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One of the difficulties of weather forecasting is that small initial errors can lead to vastly different forecasts later on. Popularly this is known as the 'butterfly effect' and describes the idea that you could take two slightly different initial temperatures, and end up with two very different forecasts, such as one for heavy rain and one for sunshine. This meant that when the researchers at ECMWF reduced the precision of the physical quantities, they had to be certain that it wouldn't result in inaccurate forecasts, taking into account a large number of scenarios, ranging from common weather patterns, to situations where the weather is highly uncertain. Fortunately, the ECMWF has a large archive of past weather data, which the researchers could try out their new 32 bit data on.

When a meteorologist prepares a weather forecast, they do not only generate a single forecast from a weather model but rather run their model multiple times in slightly different configurations. They typically run each model 50 times in what is known as an 'ensemble forecast'. This means they get 50 different predictions of the weather given starting conditions which vary only slightly from one another. On some days the forecast from all of the model runs will be very similar, indicating that there can be confidence in the forecast.

On other days the weather might be more uncertain, meaning that the small differences in the model configurations will lead to very different forecasts. This is why when you look at the daily weather forecast you are often given a percentage chance of rain – this reflects the different outcomes of the ensemble spread test. For a good weather forecast, it is not only important to know the most likely weather but also to know the uncertainty of predictions such as the chance of heavy rain in a specific area.

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The ECMWF researchers were able to try out their 32-bit data on lots of historical weather information, ensuring that they tested it on days where there had been a fairly certain forecast as well as days where the forecast had been more uncertain. The surprising finding was that reducing the precision of the measurements resulted in the same quality of forecast.

The next stage is for the researchers to try and reduce the precision down to '16 bit' which would mean using measurements which are accurate to only 3 decimal places. If this is possible then it will result in further significant improvements in weather forecasting. In order for this level of precision to be possible, it will be necessary to identify which parameters can be reduced to this level of accuracy without affecting the quality of the forecast. What may be required is to reduce the accuracy of some parameters while keeping some others at 32 bit precision, a task which will come with its own scientific challenges, but if possible will lead to a further significant advance in forecasting capabilities.

# TECHNICAL SUPPLEMENT

Most people have heard about the butterfly effect – this is the idea that the small flap of a butterfly's wings could lead to a chain of events which would make an impact on the other side of the world. In our own lives we can all think of small seemingly insignificant moments which then cause a big change of direction for us. What most people don't realise is that mathematician and meteorologist Edward Lorenz came up with the phrase 'butterfly effect'. Lorenz is the founder of a branch of mathematics called Chaos Theory, and the weather is an example of a chaotic system.

This doesn't mean it is a random system – in fact it is the opposite – the weather is governed by well known physical equations such as the Navier-Stokes Equations. If a system is chaotic it means that a small change in the initial starting conditions can result in a wildly different outcome. This is why the researchers had to prove that changing the initial data from 64 bit precision to 32 bit precision didn't result in errors which spiralled out of control and affected the forecast. Surprisingly they were able to show that the change in precision did not significantly change the forecasts, meaning that it is now possible to change to using 32 bit precision, saving on computing power.

## Links

**https://journals.ametsoc.org/doi/abs/10.1175/MWR-D-14-00110.1**
**https://www.nature.com/articles/nature14956**

## Expert

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