



Climate Variability and Weather



Short-term differences from the long-term climate, or “climate variability”, can increase the risk of damaging extreme weather events. This note examines the causes of climate variability and the use of global climate models to understand, and predict, these variations.

Background

The terms “weather” and “climate” are sometimes confused, but they are very different concepts. The weather is the local condition of the atmosphere at a particular time, including temperature, wind speed and rainfall. It varies from day to day and from season to season. The climate is a statistical summary of all the weather that occurs at a certain location over a relatively long period (30 years is often used). Climate can be expressed using averages: for example, the average temperature over a July day in central England is 16°C. Climate also includes information about probability: there is a 1 in 20 chance that the average temperature over a July day in central England will be above 20°C.¹ When low probability weather events occur they can be considered “extreme”. Differences from the long-term climate over shorter periods (a month or year for example) are known as climate variability. Such variations in climate can change the likelihood and magnitude of extreme weather events.

Natural forms of climate variability are likely to be the main influence on the UK’s climate over the next few decades.² Then, as the century progresses, the influence of increasing greenhouse gas (GHG) concentrations is likely to be of growing importance.² The Climate Change Act requires the government to adapt to long-term changes to climate; one obligation is for Defra to produce a climate change risk assessment (CCRA) for the UK every 5 years, with the first published in January 2012.³ However, there remain large

Overview

- Weather and climate vary naturally due to complex interactions between the ocean, land surface and atmosphere.
- External influences, such as greenhouse gas increases, also cause climate to vary.
- Global climate models project that greenhouse gases will cause global average temperature to increase this century. Model limitations mean there is less confidence in regional projections of climate.
- Natural forms of climate variability are likely temporarily to enhance or to mask the gradual global warming this century.
- Research is ongoing to improve shorter-term predictions of variations in climate over months and years.

uncertainties in model projections of regional changes in climate, especially for changes in rainfall.

In November 2011, the United Nations Intergovernmental Panel on Climate Change (IPCC) reported that people and assets in many countries are increasingly vulnerable to extreme weather. They noted that the nature of such extremes has changed over the past 50 years, and that further large changes are likely as this century progresses.⁴ However, exactly how the frequency and strength of extreme weather events might change is highly uncertain. Adaptation measures taken in the near future therefore need to be resilient to a broad range of future climates.³

The Climate System

Movement of air in the atmosphere occurs over a wide range of space and time scales, from a gust of wind to a monsoon. The oceans, ice sheets, vegetation and other parts of the land surface all interact with the atmosphere and thereby influence weather and climate. Together, these components make up the “climate system”. There are naturally recurring patterns of variability that result in the transfer of energy from one part of the climate system to another. The El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) are examples of this type of “internal” climate variability. There are also processes which change the total amount of energy in the climate system.^{5,6} These are known as “external” causes of climate variability.

Internal Climate Variability

El Niño/Southern Oscillation

The most prominent example of internal climate variability is year-to-year fluctuations in the temperature of the upper tropical eastern Pacific Ocean. A period of warmer water is called an El Niño; a cooler period is known as a La Niña. The corresponding fluctuations in atmospheric circulation are known as the Southern Oscillation. The combined ocean-atmosphere interaction is known as ENSO.

The effects of ENSO propagate through much of the atmosphere and cause short-term climate to vary across the world. No two ENSO events are identical, but after many years of observation, consistent patterns have emerged. Certain changes become more (or less) likely when either warming or cooling occurs (Box 1). ENSO is even large enough to change globally averaged temperature. During an El Niño episode energy moves from the ocean to the atmosphere, and the globally averaged temperature of the lower atmosphere tends to increase. During a La Niña the reverse occurs and temperature decreases.

Box 1. Regional Impacts of ENSO

- The **South Asian monsoon**, which is critical for agriculture in the region, is strongly influenced by ENSO. During a La Niña episode rains are more plentiful and flooding more common. Failed rains and drought tend to occur during an El Niño episode, though this depends upon the details of the warming pattern in the Pacific.
- There is typically less rainfall in Southeast Asia during an El Niño. Drought conditions, combined with deforestation and slash-and-burn practices, lead to **forest fires in Indonesia**. The fires release large quantities of carbon and reduce regional air quality.
- Despite occurring at the opposite side of Earth from temperature changes in the Pacific, **rainfall in East Africa** is also influenced by ENSO. In general, there is less rain during a La Niña, and more during an El Niño, but the strength of the effect varies with season, and in different parts of East Africa. Other factors, such as the temperature of the Indian Ocean, are also important.
- During the recent **strong La Niña** episode, between June 2010 and May 2011, extreme weather events occurred across the world. The floods in Pakistan (began July 2010) and drought in the Horn of Africa (began July 2011) resulted from variations in regional climate that are consistent with La Niña conditions. However, the intensity of both these events was increased because other forms of climate variability were superimposed on the ENSO effect. For example, monsoon rainfall in Northern Pakistan was enhanced by an unusually persistent weather pattern further to the north, which also caused a record heatwave, drought and wildfires in Russia.⁷

The North Atlantic Oscillation

ENSO mainly causes climate to vary in the tropics; it has only a small effect on the UK, which is more affected by another pattern of internal climate variability known as the North Atlantic Oscillation (NAO). The NAO is a measure of the difference in atmospheric pressure between Iceland and the Azores. It is closely linked to the strength and orientation of the westerly winds (the “jet stream”) on which storms grow and are guided across the Atlantic towards the UK.

The NAO has a particularly strong influence on the UK in winter. In a positive phase, when the difference in pressure is large, the jet stream strengthens and points directly towards the UK, typically leading to mild and wet winters.

During a negative phase, when the difference in pressure is small, the jet stream points towards southern Europe, and the UK is more likely to be influenced by Arctic air; such winters are therefore often colder (see Box 3).

The NAO itself can be highly variable, with changes in the pressure pattern often occurring week by week. This is one reason why the UK’s winter climate is so variable. However, one particular phase of the NAO can sometimes dominate over a season, or over successive years. For example, the negative phase was persistent during the 1960s, and the positive phase occurred frequently during the 1990s. Winter temperatures in the UK were consistent with these changes.

External Climate Variability

- **changes in solar output** The sun is the ultimate source of energy in the climate system, and cyclical changes in its output occur (one prominent cycle has an 11 year period). These changes have caused climate to vary in the past, but are not currently the dominant form of external climate variability.^{5,8} Over tens of thousands of years, variations in the Earth’s orbit also change the amount of solar energy received. The changes are small, but when amplified by changes in the climate system, they appear to trigger gradual switches between glacial and interglacial periods.
- **volcanic eruptions** After large volcanic eruptions sulphate particles can enter, and spread throughout, the upper atmosphere. They reflect incoming solar energy and thereby cool the surface for the following year or two. The most recent large eruption to affect global climate was that of Mount Pinatubo in the Philippines in 1991. Details of atmospheric circulation mean that it is less likely for eruptions outside the tropics, such as Eyjafjallajökull in Iceland in 2010, to affect global climate significantly.
- **greenhouse gas emissions** Human activities, including burning fossil fuels, release GHGs to the atmosphere. As a result, the concentration of carbon dioxide (CO₂) has increased from 280 parts per million (ppm) in 1850 to 390 ppm in 2011. The concentration of other GHGs has increased by an amount equivalent to around 75 ppm of CO₂. GHGs trap energy that would otherwise escape into space and so increase the amount of energy in the climate system. They are very likely to have caused much of the observed increase, of around 0.5°C, in globally averaged surface temperature over the last 50 years.⁵

Using Models to Estimate Future Changes

Global climate models (GCMs, Box 2) are used to try to understand both internal and external causes of climate variability and to examine how increasing GHG concentrations might change climate in the future. Such GCM simulations are typically based on a range of plausible scenarios of future GHG emissions and are therefore called “projections” rather than “predictions”. For example, GCMs project that ‘low’ GHG emissions will cause globally averaged surface temperature to rise by 1.1–2.9°C this century. In contrast, if ‘high’ emissions are assumed, the temperature rise is projected to be 2.4–6.4°C.⁵ GCMs are

also used to investigate whether patterns of internal climate variability, such as ENSO, might be changed by GHG increases. However, such changes remain highly uncertain.

Box 2. Global Climate Models

In a GCM, the atmosphere is represented on a three dimensional grid. The spacing between the points in the grid is called the 'resolution'. A typical spacing in both the latitude and longitude directions is currently around 150 km. Variables such as temperature and humidity describe the state of the atmosphere at each point in the grid. The value of those variables at a future point in time is calculated by solving known equations of fluid motions and thermodynamics. Similar calculations are made to simulate the behaviour of the ocean. Other parts of the climate system, such as polar ice caps, are also modelled. Super-computers are required to undertake the large number of calculations.

Because GCMs simulate the behaviour of the climate system in three dimensions they are able to capture large-scale features of the climate such as the jet streams, ENSO and the South Asian monsoon. However, all physical processes occurring at scales smaller than the resolution must be approximated, usually with an average value. In the real climate system, there is a two-way interaction between small- and large-scale processes so this approximation is an important source of uncertainty in GCM simulations.

Modelling Weather and Long-term Climate

As well as projecting how climate might change this century, computer models are used to predict the weather over the coming days. The models used are similar to GCMs because they aim to simulate the behaviour of the same physical system. However, there are important differences between the two types of modelling. Some of these differences illustrate the challenges facing scientists who aim to predict how climate will vary in the future.

Starting Information

A weather forecast requires an assessment of the state of the atmosphere at the start of the forecast period, which is provided by observations from around the world. The model then predicts how weather systems will evolve from this initial state in the following days. The atmosphere is a "chaotic" system; a small error in the initial state of such a system can quickly lead to a large error in a prediction of its future state. It is not possible to measure the whole atmosphere without error so accurate forecasts are limited to around a week ahead. As external influences change little over a week or two they can usually be considered constant in weather forecasts.

It is not possible to predict exact sequences of weather, or internal variability such as ENSO, many decades in advance so century-scale climate projections do not need to start from an observed state. Instead, the aim is to examine long-term climate trends caused by estimates of changing external influences, such as a GHG emission scenario.

Complexity and Resolution

The models used to predict weather need only to represent the atmosphere because other parts of the climate system change too slowly to affect forecasts. Over longer timescales the oceans, sea ice and land surface all interact with the atmosphere. As GCMs aim to project centuries into

the future they must include each component of the climate system. Due to this additional complexity, and limited computing resources, current GCMs have a coarser resolution than weather forecast models.

The relatively coarse resolution of GCMs means they do not simulate some features of atmospheric circulation as well as weather forecast models. This is one reason for the limited confidence in regional climate change projections (including rainfall patterns and extreme weather events). An example is whether very cold winters will continue to occur in the UK, despite the expected global warming. Most current GCMs project that UK winters will, on average, become warmer as the century progresses, and that very cold winters (like 2009/10, Box 3) will become less common.⁹ However, GCMs underestimate the observed frequency of weather systems which lead to cold conditions in the UK. Recent research suggests a GCM with a finer resolution of the atmosphere and ocean simulates these systems more accurately.¹⁰ The trade-off is that increased resolution requires additional computing resources.

Evaluation

Weather forecasts can be evaluated against observations every day. For example, today's 5 day forecasts are known to be as accurate as the 3 day forecasts of 20 years ago.¹¹ In contrast, GCMs have to be evaluated on their ability to simulate the current, or past, climate. A GCM should be able to simulate a climate with realistic natural variability. In addition, when the changing external influences of the past century are included, a GCM should simulate climate changes similar to those observed. Current GCMs generally perform well in such tests.⁵ Uncertainty in both weather forecasts and climate projections is assessed by performing a particular simulation many times. The chaotic nature of the climate system leads to a range of model results, which can be used to estimate the probability of various outcomes.

Box 3. Cold Winters in the UK

In the UK, the winters of both 2009/10 and 2010/11 were colder than any of the preceding decade. However, similarly cold winters have been common throughout the longer measurement record. The spells of extreme cold during these recent winters occurred when the NAO was in an unusually negative phase. Winds from the Atlantic were therefore weaker, and cold Arctic air influenced the UK. The disrupted wind patterns, and redistribution of energy around the North Atlantic basin, led to warmer than average conditions in the Mediterranean. Globally, the winter of 2009/10 was one of the warmest on record.¹² Weather in the UK, which covers only 1 part in 2000 of Earth's surface, has little impact on global averages.

Shorter Term Climate Predictions

GCMs are now being used to examine monthly to decadal timescales, which fill the gap between weather forecasts and climate projections, and could in principle provide advice on important planning timescales for energy provision, transport disruption, agriculture and fisheries, or flooding risk. The aim is to make useful forecasts of whether a particular month, season or year is likely to be warmer or colder, wetter or drier than normal. This presents the challenge of accurately simulating both internal variability

from an observed initial state (as in weather forecasts) and external variability (as in climate projections). Such simulations are considered climate predictions (rather than projections), and provide important opportunities for evaluating GCMs against observations.

Monthly and Seasonal Predictions

Monthly and seasonal forecasts are currently relatively successful in the tropics, where strong interactions between the upper ocean and the atmosphere, such as ENSO, lead to predictable variations in regional climates (Box 1). Seasonal forecasts for the UK are currently successful only when there are strong predictive signals in the starting conditions (such as the negative NAO during the cold winter of 2009/10, Box 3). However, improved winter forecasts for the UK may be possible in the future. A number of relationships between the UK's winter climate, and other processes in the climate system (including changes to atmospheric circulation caused by variations in solar output and by melting Arctic sea ice) have recently been found.¹³

Yearly and Decadal Predictions

As the timescale increases, predicting climate becomes more challenging. This is partly because relatively slow changes in ocean circulation are the dominant cause of internal variations in climate occurring over decades. As ocean observations are limited in comparison with those in the atmosphere (Box 4), predictions are started from an initial state that is likely to contain significant errors. This means that exact predictions are unlikely to be possible in the near future. One method used to evaluate decadal prediction systems is to 'predict' retrospectively (or hindcast) the climate of previous decades for comparison with available observations. Hindcasts should also help to improve understanding of the causes of variations in climate that occur over annual and decadal timescales, and that can temporarily mask or enhance the gradual global warming trend that GCMs project (see Box 4, for example).

Future Research

The Met Office Hadley Centre provides "world-leading"¹⁴ climate modelling services and advice to the government. Their projections of the UK's future climate⁹ formed the basis of Defra's first CCRA. Despite being the best projections currently available, they are subject to large uncertainties. As noted, one source of uncertainty in projections of national scale changes is the coarse resolution of current GCMs. To increase resolution, more powerful computing facilities, and the infrastructure to store and transfer increased volumes of data, are required. The government's Chief Scientific Advisor, Sir John Beddington, recently examined options for funding climate modelling and advice.¹⁴ A key conclusion of this review was "that a step-change increase in supercomputing capacity...would be required to most effectively meet the Government's key evidence and advice needs, in particular around regional climate change and extreme events".

Box 4. Measuring Changes in the Climate System

One common measure of climate is **globally averaged surface temperature**, which has increased only a little over the past decade (although, on average, the 2000s was the warmest decade to be measured directly). This is despite increasing GHG concentrations which have resulted in energy being added to the climate system.

However, this measure conceals regional changes. For example, the Arctic has continued to warm rapidly, and satellite measurements show that **summer sea ice cover** has declined by around a third over the past 30 years. It is also likely that the sea ice has become thinner.

In addition, globally averaged surface temperature accounts for only a small amount of the energy in the climate system. The entire atmosphere stores as much heat as the upper three metres of the ocean. Although ocean measurements are limited (global data for the upper 2 km have been collected only since 2000 and there are few data from the deeper ocean) it seems that **ocean heat content** has continued to rise over the past decade.

This is supported by a continuously rising **global sea level**,⁵ which has occurred partly because water expands as it warms, but also because of melting glaciers and ice sheets. Further evidence is provided by century-scale GCM climate projections which suggest energy has moved from the surface and upper ocean to the deep ocean over the past decade.¹⁵ However, there are too few measurements from the deep ocean to confirm these results, or to be sure which physical mechanisms are important.

Improved scientific understanding of the climate system will ensure that supercomputing resources are used most effectively. To address knowledge gaps, and to increase the effectiveness of technical developments, organisations such as the Met Office are focussing on using a common prediction system across all timescales, from weather forecasts, through seasonal climate predictions to century-scale climate projections.¹⁶ The rationale is that better scientific understanding of one timescale should improve predictions made over other timescales. This is due to the two-way interaction between shorter timescale changes, such as weather events or ENSO, and longer timescale changes, such as those caused by GHG increases.

Endnotes

- 1 Met Office Hadley Centre central England temperature data. Available from: <http://www.metoffice.gov.uk/hadobs/hadcet/data/download.html>
- 2 Hawkins and Sutton, *Bulletin of the American Meteorological Society*, 2009.
- 3 *The Climate Change Risk Assessment*. See: <http://ccra.defra.gov.uk/>
- 4 IPCC, *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, Summary for Policy Makers, 2011
- 5 IPCC, *4th Assessment Report*, Working Group I, 2007
- 6 The Royal Society, *Climate Change: a summary of the science*, 2010
- 7 See, for example, the *ECMWF Autumn 2010 Newsletter*
- 8 Gray *et al.*, *Reviews of Geophysics*, 2010
- 9 *The UK Climate Projections 2009 (UKCP09)*. Available from: <http://ukclimateprojections.defra.gov.uk/>
- 10 Scaife *et al.*, *Geophysical Research Letters*, 2011.
- 11 See, for example, the *ECMWF Annual Report of 2010*
- 12 Osborn, *Weather*, 2011
- 13 Summarised in: J. Slingo, *Briefing on the likelihood of severe winter weather over the next 20-30 years for Sir John Beddington*, 2010
- 14 Reviews available from: <http://www.bis.gov.uk/go-science/science-in-government/global-issues/climate-change>
- 15 Meehl *et al.*, *Nature Climate Change*, 2011
- 16 See, for example, the *Met Office science strategy 2010-2015*