THE ROYAL SOCIETY

Earth's future climate

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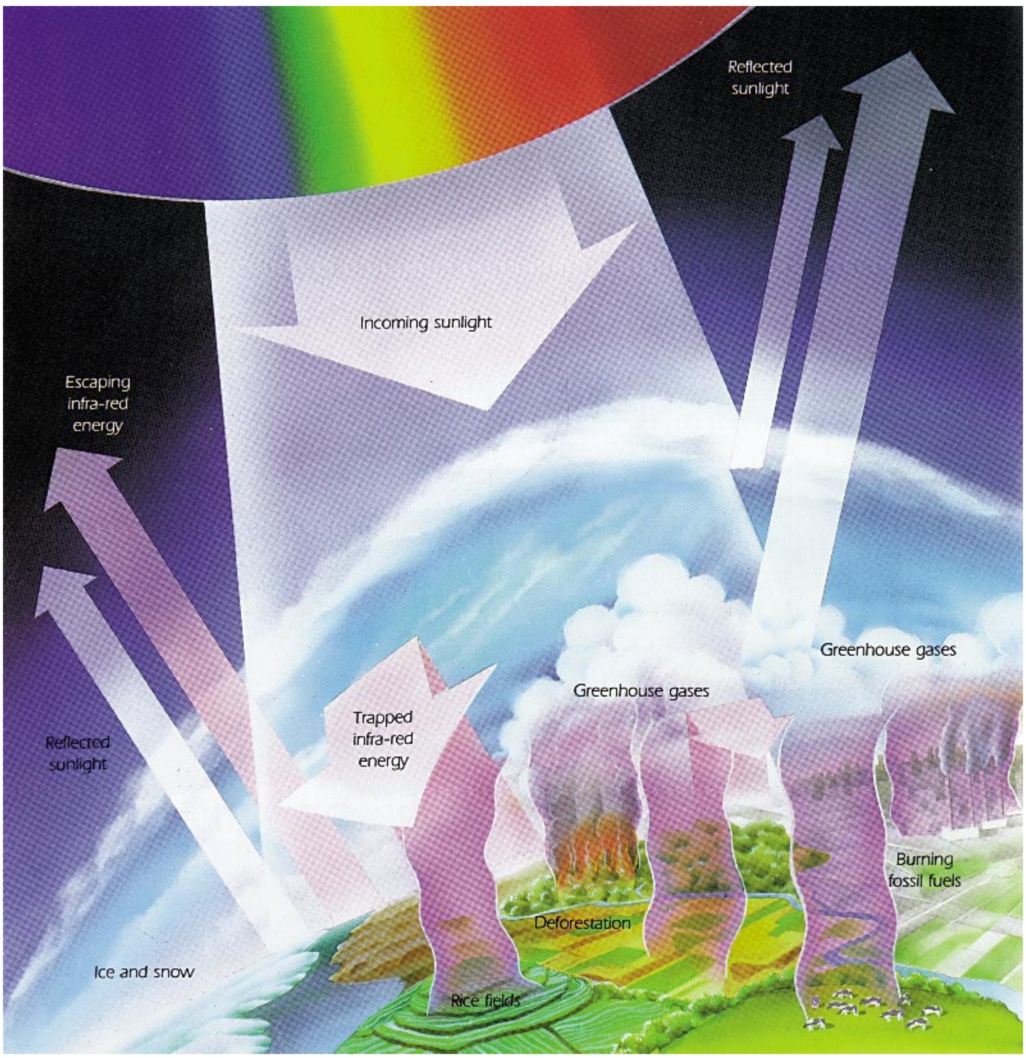

The enhanced greenhouse effect. The Earth's surface temperature is slowly rising due to human activities, which are releasing heat-trapping gases, notably carbon dioxide and methane, into the atmosphere. By 2100 this temperature rise is expected to reach $2 \pm 1\,^{\circ}\mathrm{C}$, other climatic influences remaining constant. This will be the fastest rate of climate change the Earth has experienced since the start of modern civilization 10 000 years ago. (Figure from Pringle (1988), used with permission of Hodder and Stoughton Limited.)

Climate change occurs on time-scales ranging from annual changes associated with El Niño, through decadal changes, to multidecadal trends linked to global warming. It affects us all in our daily lives, impacts the performance of much of industry, and leads to billions of pounds of damage worldwide each year. In many countries the general public is becoming concerned as press reports, personal experience and anecdotal information all point to an increase in the frequency and severity of extreme weather events linked to climate change. Many opinions have been expressed on the subject from the doomladen to the dismissive. This paper aims to state clearly the current scientific position on climate change, and to provide informed scientific projections for Earth's climate into the next millennium. This will help decision makers, managers of weather risk, and all with an interest in our future climate.

Keywords: climate; global warming; El Niño; extreme weather; hurricane; storm

1. Introduction

Climate and weather affects us all in our daily lives and at least 70% of industry. By 'climate' we mean the average state of the weather over periods ranging from months to centuries. In recent years the phrase 'climate change' has become familiar as environmental extremes regularly hit the headlines. Let us begin by defining the meaning of 'climate change'.

The United Nations Framework Convention on Climate Change uses the term to describe change brought about only by human activities, in particular by those processes that emit the heat-trapping gases carbon dioxide and methane into the air. A more generic usage, common in the scientific community, refers to change brought about by any source, human as well as natural. Here we use 'climate change' in its widest sense to describe any change in the Earth's climate on time-scales longer than a few months. Thus we consider (a) interannual (year-to-year) climatic changes linked to natural variability caused, for example, by El Niño, La Niña, the North Atlantic Oscillation or volcanic eruptions, as well as (b) multidecadal trends linked to anthropogenic (human-induced) global warming or to solar intensity changes. On the interannual to decadal level, natural climatic variability has a far greater impact on local climate than long-term trends due to global warming. However, on the multidecadal ($\geqslant$ 50 years) level, changes in the mean climate due to global warming could, in certain regions, start to approach the limits of current natural variability.

Are weather-related disasters becoming more common as the news headlines often indicate? We examine this by considering the statistics on natural catastrophes reported by insurers and reinsurers. For the recent 10-year period (1988–1997), the economic (i.e. total) and insured losses due to natural catastrophes have averaged £40 billion and £8 billion per year, respectively. Windstorms alone (hurricanes, winter storms and tornadoes) account for 30% of these economic losses and for 70% of the insured losses. In 1998, for example, the devastation brought by Hurricane Georges in the Caribbean and US (see figure 1) proved the largest insured loss of the year and the third most costly in American insurance history. Since 1970, the number and cost of natural catastrophes have risen continuously. A comparison of 1988–1997 with the decade 1970–1979 shows that the number of major natural catastrophes, and their resulting economic losses and insured losses, have increased by factors of 3.0, 4.3 and 5.8, respectively (figures inflation adjusted; Swiss Re. 1998). The largest rises

Figure 1. Residents in Key West, Florida, fleeing Hurricane Georges on 26 September 1998. Georges claimed the lives of 4000 people across the Caribbean, caused economic damages of £6.3 billion (second highest natural catastrophe loss of the year) and insured losses of £2.1 billion (largest of the year). (Image used with permission of Associated Press.)

have occurred since the late 1980s. Most of the loss increases may be explained by socio-economic factors such as a higher density of population in hazard-prone areas, and by more assets being insured in hazard areas. However, it seems unlikely that the three-fold increase in the number of major natural disasters can be due merely to improved reporting. Many insurers feel that the frequency of extreme events has genuinely increased and that long-term climate change could be a contributory factor.

A number of informative and influential summaries on the effects of anthropogenic global warming have appeared in recent years. Foremost is the 1996 comprehensive report by the Intergovernmental Panel on Climate Change (IPCC 1996), an international panel of eminent climatologists working on behalf of the United Nations. Others include those by Houghton (1997), Karl *et al*. (1997), Saunders (1998) and Hulme & Jenkins (1998). This review builds on and extends these summaries by treating climate change in its broadest sense (i.e. considering the impact of natural variability in addition to long-term global warming trends), and by including new research on hurricane trends and extreme weather event prediction.

2. Types and causes of climate change

For brevity we consider two types of climate change: those producing interannual change, and those producing multidecadal trends. Year-to-year changes in climate, especially those linked to changing temperature, rainfall and windspeed impact much of industry. It is also important to recognize and plan for long-term trends. Although these perforce allow governments and industry more time to respond, thereby minimizing human and financial impacts, reaction times are often long. Furthermore, slow multidecadal climate trends may also affect interannual variability, as suggested recently with regard to El Niño frequency (Timmermann *et al*. 1999).

(*a*) *Interannual changes*

The three most important classes of natural variability of the Earth's climate are those associated with El Niño/La Niña, the North Atlantic Oscillation (NAO), and major volcanic eruptions.

(i) *ENSO and NAO*

El Niño and its cold-episode sister La Niña are the strongest interannual climate signals on the planet. Global damage estimates for the 1997/98 major El Niño event exceed £20 billion. Archaeological evidence suggests that El Niños and La Niñas have been occurring for at least 15 000 years (Rodbell *et al*. 1999). The clearest sign that an El Niño (La Niña) event is underway is the appearance of unusually warm (cold) water between the Date Line and the coasts of Ecuador and Peru. During the 1997/98 event, for example, waters in this region were *ca.* 5 °C warmer than usual. However, El Niño (La Niña) is more than just a warming (cooling) of the eastern tropical Pacific, it is a perturbation of the ocean–atmosphere system; hence it is also called ENSO (El Niño Southern Oscillation), where the Southern Oscillation refers to the accompanying large-scale seesaw oscillation in atmospheric pressure between the Pacific and Indian Oceans.

ENSO's natural variability is illustrated in figure 2 (top time-series), which shows the frequency and duration of El Niño (positive departure) and La Niña (negative departure) events since 1950 based on a new multivariate ENSO index (Wolter & Timlin 1998). The large year-to-year changes are clear, as is the trend since about 1980 towards more El Niños and fewer La Niñas. Defining major ENSO events as having a standardized departure greater than 1 or less than −1, one obtains an average return period of *ca.* 4 years. Thus, approximately every 4 years, abnormal patterns of temperature, rainfall and storminess occur around the globe due to ENSO. The amplitude of many of these climate anomalies currently exceeds the mean changes likely by 2100 due to anthropogenic global warming.

The NAO is the major source of interannual variability in the atmospheric circulation over the North Atlantic and surrounding land masses. It is defined in terms of the pressure difference between Iceland and the Azores. Year-to-year and decadal changes in the NAO are linked to seasonal changes in regional temperature, rainfall and storm occurrence over Europe and, to a lesser degree over northeastern Canada and the eastern USA (Hurrell 1995). Unpublished research by the author shows the NAO is linked directly to 50% of the year-to-year variability in UK winter storminess, to 50% of the winter rainfall in Scotland, Spain and parts of Norway, and to 40% of the winter temperature anomalies over much of western Europe. The NAO's historical variability is shown in figure 2*b*. As with ENSO, substantial year-to-year and decadal variability is apparent. The oscillations in local winter climate linked to the NAO currently exceed the projected changes in mean climate expected from global warming by 2100.

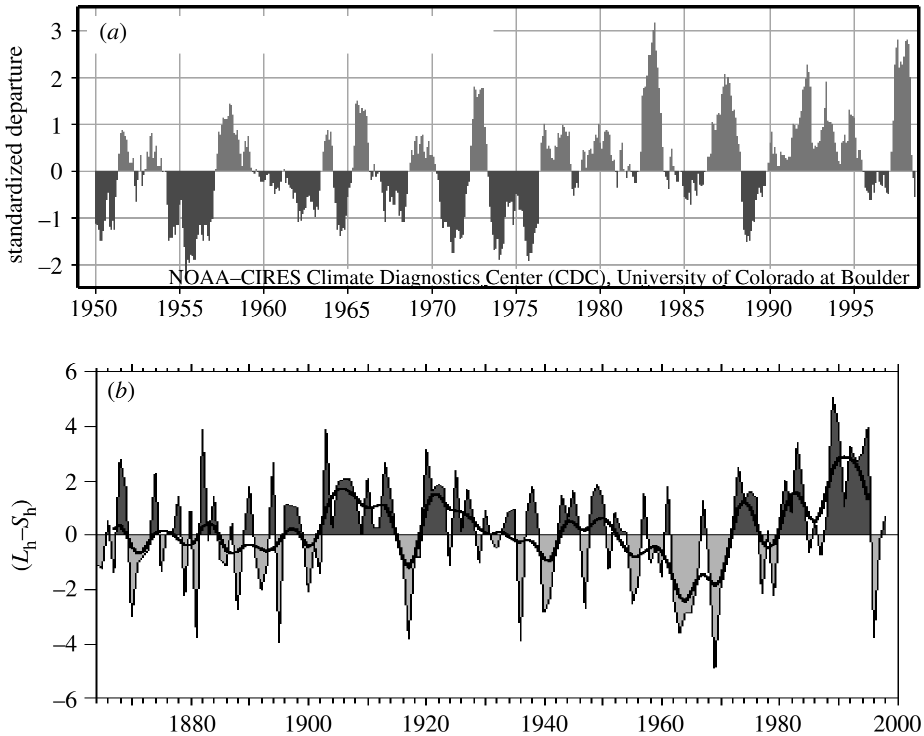

Figure 2. (*a*) ENSO time-series 1950–1998 (Wolter & Timlin 1998). (*b*) North Atlantic Oscillation Index time-series for December–March 1864–1998. The multivariate ENSO index is a weighted average of the main ENSO features contained in six variables: sea-level pressure, the east–west and north–south components of the surface wind, sea surface temperature, surface air temperature and total cloudiness. The NAO index is the anomaly (millibars) in mean pressure difference between Iceland and the Azores. Both ENSO and NAO exhibit substantial year-to-year and decadal natural variability.

(ii) *Volcanic eruptions*

Volcanic eruptions are also an important source of natural climate variability. Major explosive eruptions can inject dust and sulphate aerosols (microscopic solid particles of diameter 10^{-3}–10^{-6} m) to heights of 20 km in the stratosphere. These particles reflect solar radiation and have a lifetime of over a year. The net effect is a cooling of the Earth's surface. The eruption of Mount Pinatubo in the Philippines in June 1991 stands out from a climatic point of view as one of the most important eruptions this century. During 1992, global surface temperatures cooled by 0.3–0.5 °C due to the eruption. The eruptions of Krakatoa (1883) and Tambora (1815) also led to global climate cooling. Indeed, 1816 has been called the 'year without a summer' when crops failed in Europe and the USA.

(*b*) *Multidecadal trends*

The two most important factors influencing future long-term trends in the Earth's climate on a time-scale of 10–1000 years are anthropogenic global warming (the enhanced greenhouse effect) and changing solar output. The effect of changes in the Earth's distance from the Sun and changes in the tilt of the Earth's poles towards the Sun—which have periods of *ca.* 100 000, *ca.* 41 000 and *ca.* 22 000 years and are believed to be a major contributory factor to ice ages (Milankovitch 1941)—will not be significant on this time-frame.

(i) *Enhanced greenhouse effect*

The basic cause of global warming is described in terms of the enhanced greenhouse effect. The Earth has a natural greenhouse effect, which keeps the planet's surface 33 °C warmer than it would otherwise be; at an average temperature of 15 °C rather than −18 °C. This greenhouse warming is due to atmospheric gases (called greenhouse gases) that trap parts of the Earth's surface infrared heat which is trying to escape into outer space. The main natural greenhouse gases are water vapour, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The enhanced greenhouse effect comes from an increase in the concentration of these natural greenhouse gases due to human activities. This increase has been taking place since the start of the Industrial Revolution in *ca.* 1765. The order of importance in contributing to human-induced global warming is CO_2 (70%), CH_4 (20%) and N_2O(10%). Quantities of these greenhouse gases are increasing steadily in the atmosphere due to fossil fuel burning (coal, oil and natural gas), deforestation, and rice cultivation. The use and production of energy accounts for *ca.* 60% of global greenhouse emissions, the burning of forests contributes *ca.* 10%, and rice fields and decaying rubbish a further 10%. The basic principles of the enhanced greenhouse effect are illustrated in the image on p. 3459.

The main reason for CO_2 having the greatest potency of all the human-caused greenhouse gases is its persistence: CO_2's lifetime in the atmosphere is *ca.* 100 years. CO_2 atmospheric concentrations have increased since the pre-industrial period from *ca.* 280 ppmv (parts per million by volume) to *ca.* 360 ppmv in 1997. We know this from analysis of ice cores and, since the late 1950s, from precise, direct measurements of atmospheric concentration. That the observed increase in atmospheric CO_2 comes from anthropogenic activity is evident from the close agreement between the long-term rise in atmospheric CO_2 and the increase in CO_2 emissions. The latter now stands at over 6000 million tonnes of carbon dioxide annually.

Temperatures have not increased as much as one would expect from the observed CO_2 increase. The reason for this is thought to be the mitigating effect of industrial aerosols, especially sulphate aerosols. These differ from the aerosols we are familiar with in our daily lives, such as those in hairsprays. They are microscopic solid particles injected into the atmosphere by either natural events such as dust storms and volcanic eruptions, or by anthropogenic activities such as fossil fuel and biomass burning, and changing land use. By blocking incoming solar energy, these aerosols act to cool surface temperatures and thus mitigate global warming. The main anthropogenic industrial source of aerosols comes from sulphur dioxide (SO_2), which is released into the atmosphere from fossil fuel burning. Once in the atmosphere SO_2 is converted into sulphate aerosol particles. In contrast to CO_2, aerosols have short atmospheric residence times of less than a week and thus are concentrated near their sources. Research by the Hadley Centre for Climate Prediction (Bracknell, UK) and other modelling groups shows that aerosols will not globally cancel global warming

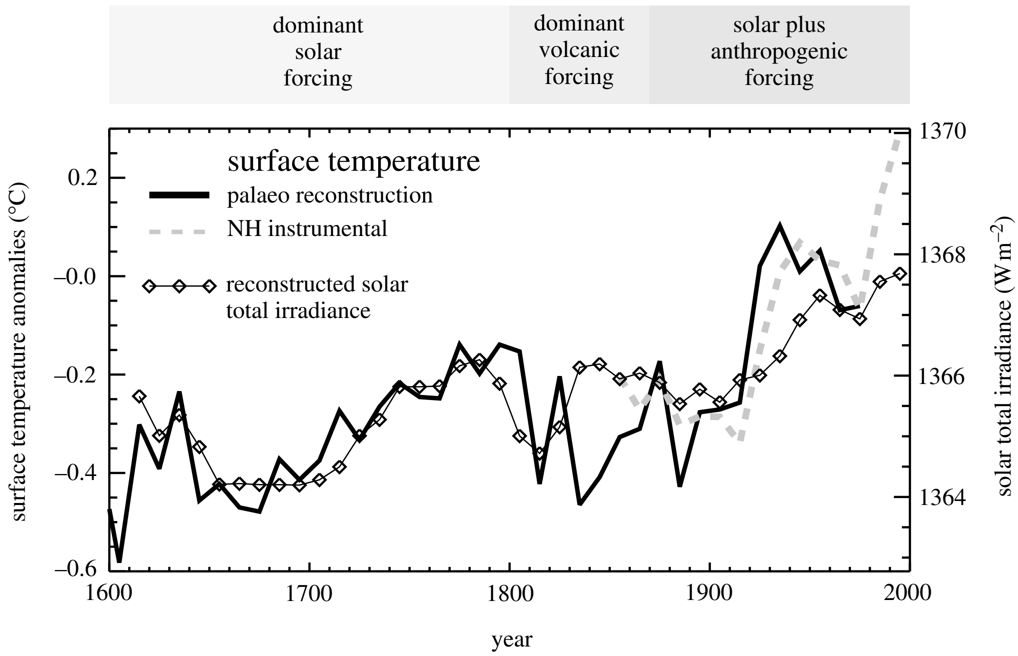

Figure 3. Comparison for 1600–1995 of the reconstructed solar total irradiance with the reconstructed Northern Hemisphere surface temperature record. Before 1860, the latter is based largely on tree ring growth. Changing solar radiation can explain most of the long-term changes in temperature before the Industrial Revolution, but cannot account for the rise in temperature since 1970. (From Lean 1997.)

but could offset locally a significant amount. Despite this, uncertainties remain in estimating the global and regional climatic impact of aerosols.

(ii) *Solar influences*

Changes in the Sun's radiative output also cause long-term climate change. The impact of this on the Earth's current and past climate has been the subject of recent research. Space-based radiometers have been monitoring solar radiative output since 1978. Based on these records, Frohlich & Lean (1998) conclude that changing solar irradiance has contributed little to the 0.2 °C rise in global mean surface temperature since 1986. This confirms the similar finding by Lean (1997) reproduced in figure 3. Lean finds the Sun can explain at best just 0.07 °C (18%) of the observed 0.4 °C rise in global temperatures since 1970. Figure 3 also shows that Lean's reconstructed solar and climate time-series correlate strongly over previous multidecadal and centennial time-scales. In particular, during the period 1610–1800, which includes the Maunder Minimum, the correlation is 0.86. This implies a dominant solar forcing of climate at this time.

3. Evidence for 20th century global climate change

This section describes the changes in global temperature, precipitation, sea level and weather extremes that have been observed during the 20th century.

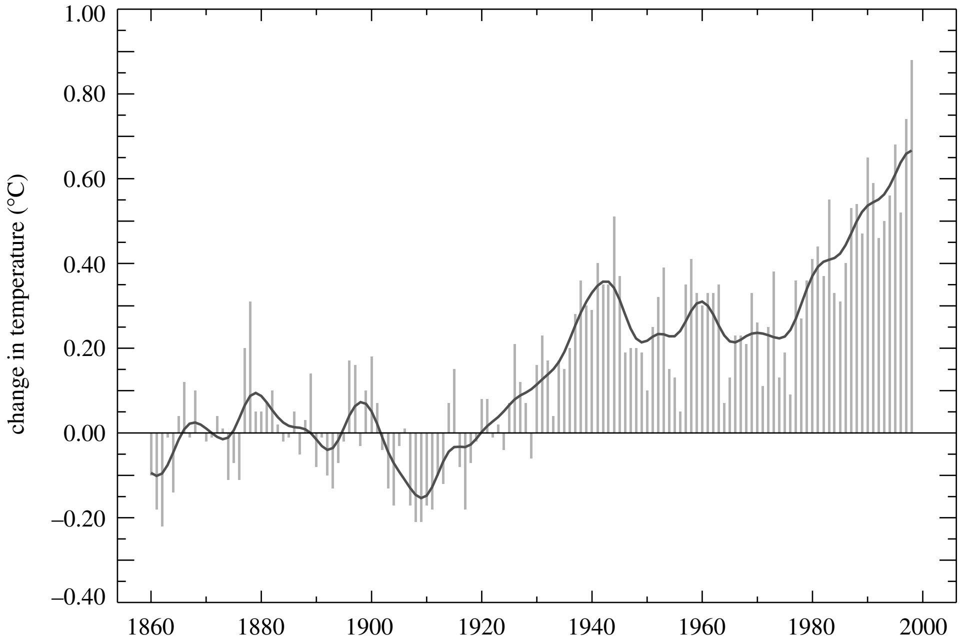

Figure 4. Global annual surface temperature variations from 1860 to 1998. Values are shown as departures (°C) from the mean at the end of the 19th century. The solid smoothed curve is obtained using a 21-year filter. Mean global temperatures are now higher than at any time since 1400. (Figure courtesy of the Hadley Centre for Climate Prediction and Research, Bracknell, UK.)

(*a*) *Climate warming*

Reliable global temperature records extend back to 1860. These are obtained by combining land temperatures recorded by weather stations chosen for their reliable observations, with sea surface temperatures estimated by processing all the available worldwide ship observations (about 60 million since 1860). The observations are then located within grid squares, say 1° of latitude by 1° of longitude over the Earth's surface. Observations within each square are averaged; the global average being obtained by averaging (after weighting by area) all the individual square averages. The uncertainty in global temperature change from 1860 to the present is less than 0.15 °C (IPCC 1996). Figure 4 shows the change in global mean surface temperature from 1860 through to 1998. The temperature has increased by 0.6–0.7 °C since the late 19th century, and by 0.4 °C over the past 25–30 years, the period with most reliable data. The warming has occurred largely during two periods, between 1910 and 1940, and since the mid 1970s. 1998 was easily the warmest year ever (followed by 1997 and 1995), and 14 of the 15 warmest years on record have now occurred since 1980. The warming trend has not been uniform; for example, the continents between 40° N and 70° N in winter and spring have warmed most, and a few areas such as the North Atlantic Ocean have even cooled. The scientific consensus (e.g. Tett *et al.* 1999) is that the global warming since 1970 is due largely to anthropogenic causes.

Various indirect evidence supports the recent warming of global temperature. For example, Alpine glaciers have lost over 1/3 of their surface area and well over 1/2 of their volume this century. This retreat is consistent with a warming in Alpine regions of 0.6–1.0 °C (IPCC 1996). The observed 10% decrease in Northern Hemisphere spring snow cover since 1975 is also consistent with a warming Earth. Furthermore, the timing of the seasons is changing in a manner consistent with the effects of global warming. Compared with 15 years ago, spring is arriving more than a week earlier at latitudes above 45° N (Myeni *et al.* 1997).

(*b*) *Is the 20th century warming unusual?*

In order to establish whether the 20th century warming is caused by anthropogenic factors or is part of the natural variability of the climate system, it is helpful to examine climate changes that have occurred in the past. The available evidence indicates that recent decades have been the warmest in the past 600 years. Before 1400, data are insufficient to make hemispheric temperature estimates, but regional estimates are possible based on pollen data and marine plankton. These indicate that the 20th century warming is indeed unusual with the Earth having been this warm less than 10% of its geological lifetime. Furthermore, an additional warming of 1–2 °C would make the Earth the warmest it has been in 150 000 years.

A sceptic may wonder how much reliance can be placed on ancient historical data. Confidence that the deduced temperature variations are indeed real comes from indirect information such as the painting in figure 5. This picture was painted in the early 17th century during the Little Ice Age when global temperatures were *ca.* 1 °C colder than they are now. Winter freezes were characteristic of the time, with skating and frost fairs regular features on European canals and rivers. Such events are, of course, now rare. The winter of 1894–95 was the last occasion, for example, when the River Thames froze sufficiently to allow an ice fair.

(*c*) *More precipitation*

Surface warming increases evaporation and the amount of water vapour in the atmosphere. There is thus a greater potential for increased global rainfall. Recent analyses of global precipitation changes during the 20th century (Karl *et al.* 1997) reveal that rain plus snowfall have indeed increased overall, and by 10% or more in many mid- and high-latitude regions. Dai *et al.* (1997) report that global precipitation has risen by over 2% during the 20th century, which is equivalent to an extra 22 mm of annual rainfall everywhere. This increase has occurred mainly during the winter season. However, not all parts of the world have seen a precipitation increase since 1900. In the African Sahel and Indonesia, for example, rainfall has decreased.

(*d*) *Sea level rise*

Over the past 100 years global sea level has risen by between 10 and 25 cm based on analyses of tide gauge records and allowing for uncertainty due to vertical land movements. It is likely that much of this rise is due to the increase in global temperature since 1900. The warming and consequent thermal expansion of the oceans may account for 2–7 cm of the observed rise, while the retreat of mountain glaciers and ice caps may account for a further 2–5 cm (Warrick *et al.* 1996). Other factors such as the contribution from the huge ice sheets of Greenland and Antarctica are more uncertain.

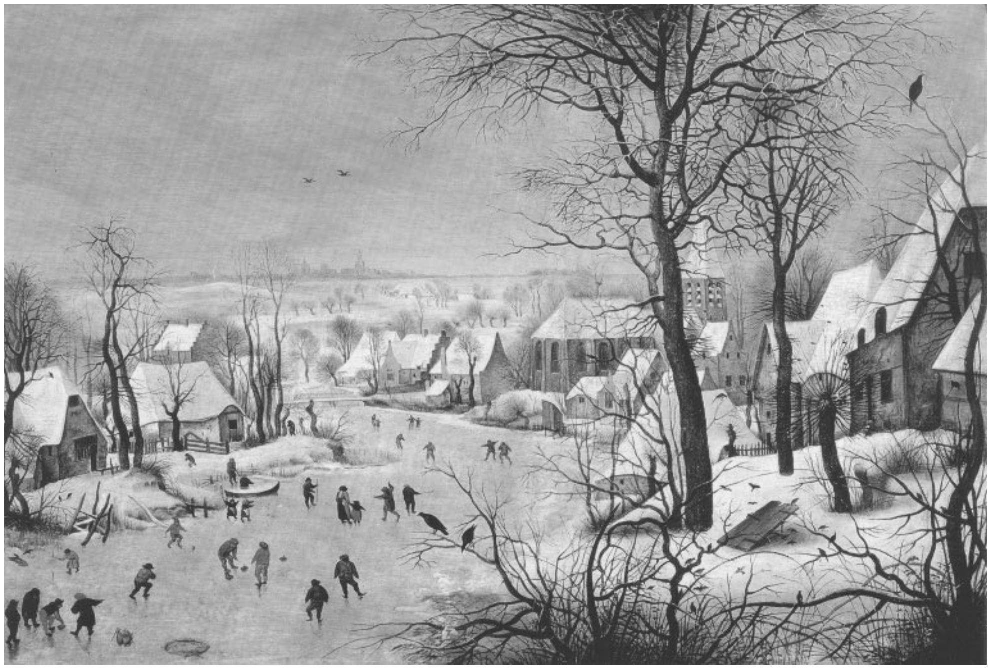

Figure 5. *Winter Landscape*, painted in 1601 by Peter Brueghel the Younger showing skaters on the frozen canals of Holland. The cold winters necessary for the canals to freeze were regular features of this time (the Little Ice Age). Skating on these canals has now become a rare event due to rising global temperatures. (Figure courtesy of the Kunsthistorisches Museum, Vienna, Austria. Erich Lessing/Art Resource.)

(*e*) *Changing weather extremes*

Is there evidence for trends in the global and/or regional number and intensity of hurricanes and floods in recent decades?

The IPCC (1996) concludes, based on the limited available evidence, that no trends have been observed in the global number of hurricane and intense hurricane strength tropical cyclones (TCs). However, new research by the author and F. P. Roberts (Roberts & Saunders 1999), using the latest available data, shows that for the period 1969–1998 significant upward trends exist in the annual numbers of these events for the three main regions of the Northern Hemisphere TC activity combined (figure 6). They also show that the annual number of Northern Hemisphere *landfalling* and 'high impact' TCs has increased over the same period (most rapidly since 1985) and that an increasing proportion of TCs are reaching intense hurricane strength. It is unlikely that biases in the data are responsible for these increases. The influence of global warming on these trends has yet to be determined but it seems more likely that they arise from multidecadal natural variability.

Further research conducted since the IPCC (1996) report shows evidence for extra-tropical windstorms in the North Atlantic having increased in intensity in recent decades. Using pressure gradients to determine windspeed, Alexandersson *et al.* (1999) find that during the 1980s and early 1990s, winter windspeeds over the northern UK and Norwegian sectors reached their highest levels since the 1920s. Whether

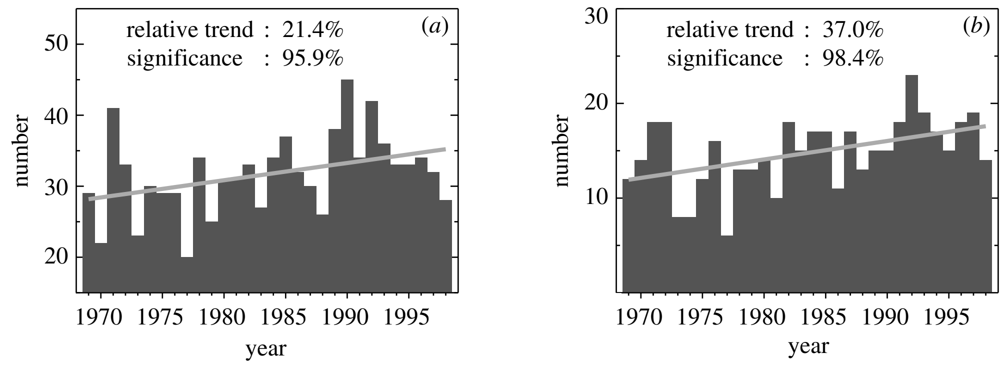

Figure 6. Time-series for 1969–1998 of the number of hurricane-strength (maximum sustained wind greater than 33 m s^{-1}) (*a*), and intense hurricane strength (maximum sustained wind greater than 50 m s^{-1}) (*b*) tropical cyclones for the three main Northern Hemisphere basins combined. The trend lines are based on a Poisson fit and are significant at the 95% level. (From Roberts & Saunders 1999.)

this rise is related to anthropogenic global warming or is connected to the 100-year cycle suggested by Lamb (1991) remains to be determined.

In addition to the increase in total precipitation since 1900 noted in § 3 *c*, various studies based on data from the USA, areas of Europe, South Africa, the former Soviet Union, Australia and Japan, all support an upward trend in the proportion of the total in the extreme precipitation category (greater than 50 mm per day). In the USA, for example, this percentage has increased from less than 8% in 1900 to more than 10% now. This trend has been been linked (Karl & Häeberli 1997) to the recent increase in the number of USA floods, a notable example being the devastating Mississippi flood in the summer of 1993. One might expect that susceptibility to flooding and flash floods in the other countries listed above may also be rising, but research results on this are not yet available.

4. Predicted future climate change

This section describes the 'best estimate' projections for how the Earth's climate will change due to global warming by 2100. Forecasts cannot be made with any certainty beyond this time.

(*a*) *Basis for confidence in predictions*

Predictions of climate trends due to anthropogenic global warming are made by sophisticated climate models. These models describe mathematically and physically the different coupled parts of the climate system; namely, the atmosphere, ocean, land and ice sheets. Climate modelling is a rapidly growing science, and only since 1985 have results been sufficiently comprehensive and credible to be taken seriously by policy makers. Furthermore, only since 1989 have computers been powerful enough to allow the development of coupled ocean–atmosphere models, which are crucial for precise climate prediction. Although much remains to be done to narrow the uncertainty of model predictions, there are sound grounds for confidence that current climate models are able to simulate important aspects of anthropogenic climate change (Carson 1999). This confidence comes from the success of models in simulating aspects of previous known climate change.

(*b*) *Temperature*

If the concentration of atmospheric greenhouse gases continues to rise at the current 0.7% annual rate, the 'best estimate' consensus of the major climate models is that global mean surface temperatures will rise by *ca.* 2 °C between 1990 and 2100. This projection takes into account the effects of future changes in aerosols and the delaying effects of the oceans. The oceanic inertia means that the Earth's surface and lower atmosphere would continue to warm by a further 1–2 °C even if greenhouse gas concentrations stopped rising in 2100. The range of uncertainty in the global warming projection to 2100 is 1–3.5 °C. A 1 °C rise would be larger than any century-scale trend in the past 10 000 years.

Regional and seasonal warming predictions are less certain. Although most areas are expected to warm, some will warm much more than others. The largest warming is predicted for cold northern regions in winter (figure 7). This is because snow and ice reflect sunlight so less snow means more heat is absorbed from the Sun, which enhances any warming; a strong positive feedback effect. By the year 2100, parts of northern Canada and Siberia are predicted to warm by up to 10 °C in winter, but by less than 2 °C in summer. Land areas are projected to warm faster than the oceans and coastal zones (figure 7). The reason is simply the higher heat capacity of the ocean, which prevents the sea surface from warming as fast as the land.

Another consequence of global warming would be an increased probability of heat waves. In the case of central England, for example, the probability of extremely hot summers such as 1995 would increase by a factor of 25 by the year 2050. In other words, summers as hot as 1995 would occur every three years instead of every 75 years (based on 1961–1990 data).

(*c*) *Rainfall*

Enhanced evaporation will intensify the global hydrological cycle, leading to a global precipitation increase of between 3 and 15% by 2100 (figure 8). Although trends at local levels are less certain, some areas such as southern Europe in summer and Australia are expected to see a decrease in precipitation. Models agree in predicting an annual precipitation increase of $15\pm10\%$ over many northern high-latitude regions (figure 8), this increase being mainly during winter. A high spatial resolution model prediction for the UK and northwest France is shown in figure 9. Mean winter precipitation is shown for the 2020s and 2050s expressed as a percentage change from the 1961–1990 average. Winters are significantly wetter throughout the UK, and by up to 10% in southeast England by the 2050s.

(*d*) *Sea level*

The Earth's average sea level is predicted to rise *ca.* 50 cm by 2100. The uncertainty range is large, 15–95 cm, and changing ocean currents could cause regional sea levels to rise much more or much less than the global average. About 70% of this rise will come from thermal expansion of the upper layers of the ocean as they warm. Melting Alpine glaciers will contribute a further 20% of the rise. The Greenland and

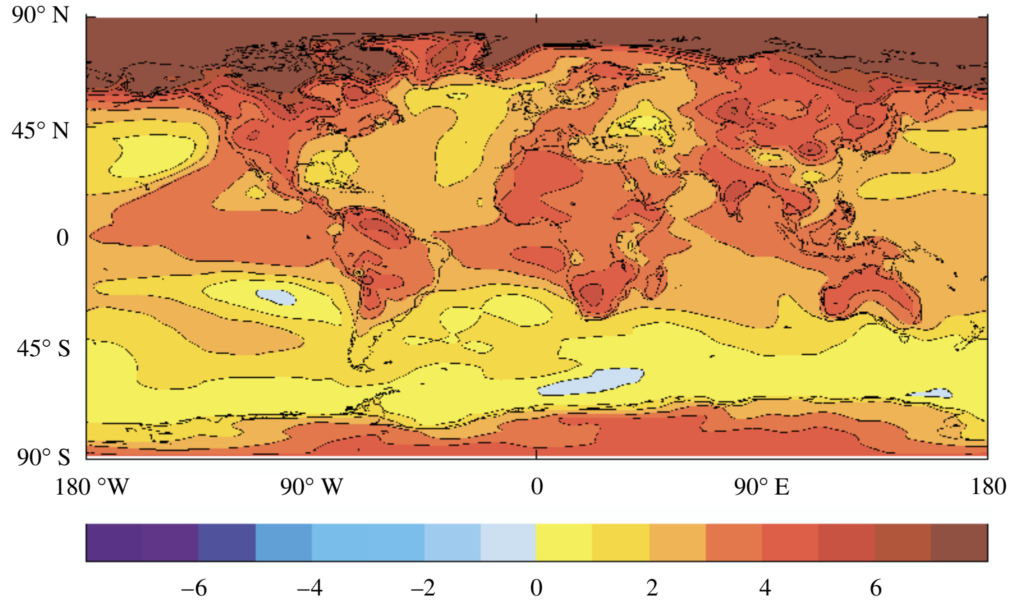

Figure 7. Change in surface temperature (°C) predicted by a climate model between 1990 and 2090 due to changes in greenhouse gases and aerosols. The figure is for Northern Hemisphere winter months. (Figure courtesy of the Hadley Centre for Climate Prediction and Research, Bracknell, UK.)

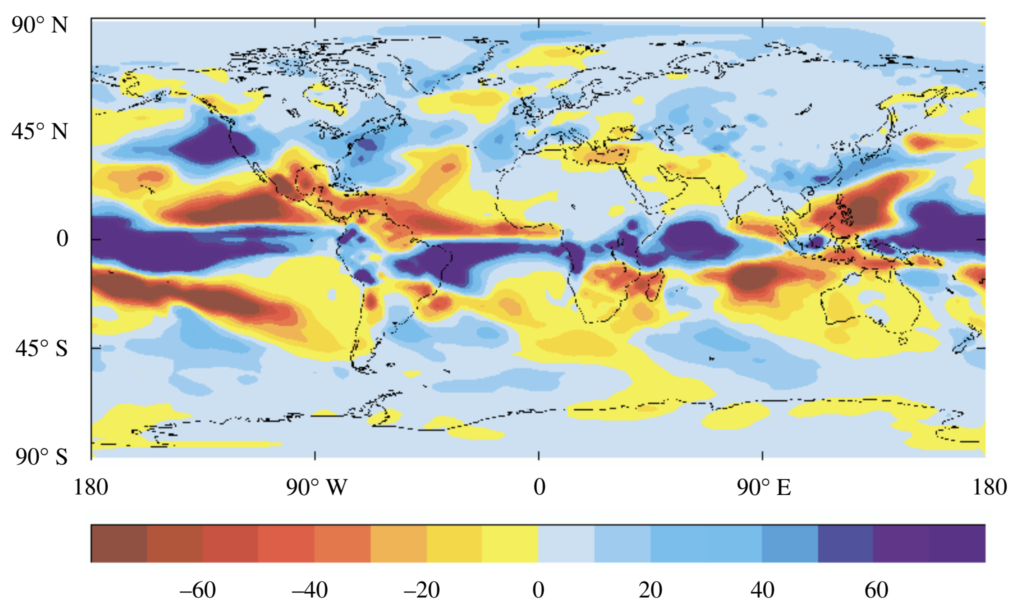

Figure 8. Percentage change in annual precipitation predicted by a computer model between 1990 and 2090 due to changes in greenhouse gases and aerosols. (Figure courtesy of the Hadley Centre for Climate Prediction and Research, Bracknell, UK.)

Antarctic ice sheets are not expected to contribute significantly to sea level rise as their melting will be balanced by increased snowfall in both regions. As the warming penetrates deeper into the oceans, sea level will continue rising well after surface temperatures have levelled off.

(*e*) *Weather extremes*

The future prospects as regards windstorms are unclear. Current climate models, of grid size *ca.* 2°, lack the spatial resolution to properly simulate tropical storms and hurricanes and are thus unable to make worthwhile long-range projections. Simple physical arguments based on the likelihood of increased convection suggest a possible intensification of tornado activity in a warmer world. Current thinking also suggests, with milder winters, an increase in the frequency and severity of European windstorms. In cold winters, a strong high pressure system forms over the cold snow-covered regions of central and eastern Europe. This acts as an effective barrier to deflect advancing Atlantic storms away from Europe. However, in mild winters, as seen in the 1980s and early 1990s, this stationary high pressure is weakened or forced eastwards, thus allowing Atlantic storms to impact Europe. Models suggest that windspeed return periods will generally shorten over the northern UK in winter, with a daily mean wind speed of $18\ \mathrm{m\,s^{-1}}$ changing from a one-in-two year event to an annual event by 2050. Over the southern UK, little change in return periods is expected for the strongest winds.

The future prospects with regard to flooding are clearer. Climate models agree on an increasing tendency for more intense but less frequent precipitation in a warmer world. In many areas, the frequency of days with precipitation of high intensity will increase at the expense of days with precipitation of low intensity. This shift in precipitation intensity will lead to more floods, and arguably to more massive storms and hailstorms. Thus images such as the one in figure 10 could become more common in a warmer world.

(*f*) *Can we change the course of climate change?*

While the natural variability associated with ENSO and other seasonal to decadal climate changes cannot be altered realistically at present, we can alter the course of anthropogenic global warming. The cuts in greenhouse gas emissions agreed by industrialized countries at the United Nations Convention on Climate Change in Kyoto in December 1997, to levels 5.2% below 1990 concentrations by 2008–12, though welcome, will have little impact on slowing climate change. Global reductions in carbon dioxide emissions of *ca.* 60% are necessary to prevent greenhouse gas concentrations from rising still further.

5. Current improvements and future challenges

This section describes recent advances in forecasting interannual variability, especially in relation to extreme weather events. Speculations are offered for long-term climate change beyond 2100. The section concludes by reviewing the major challenges facing climate science.

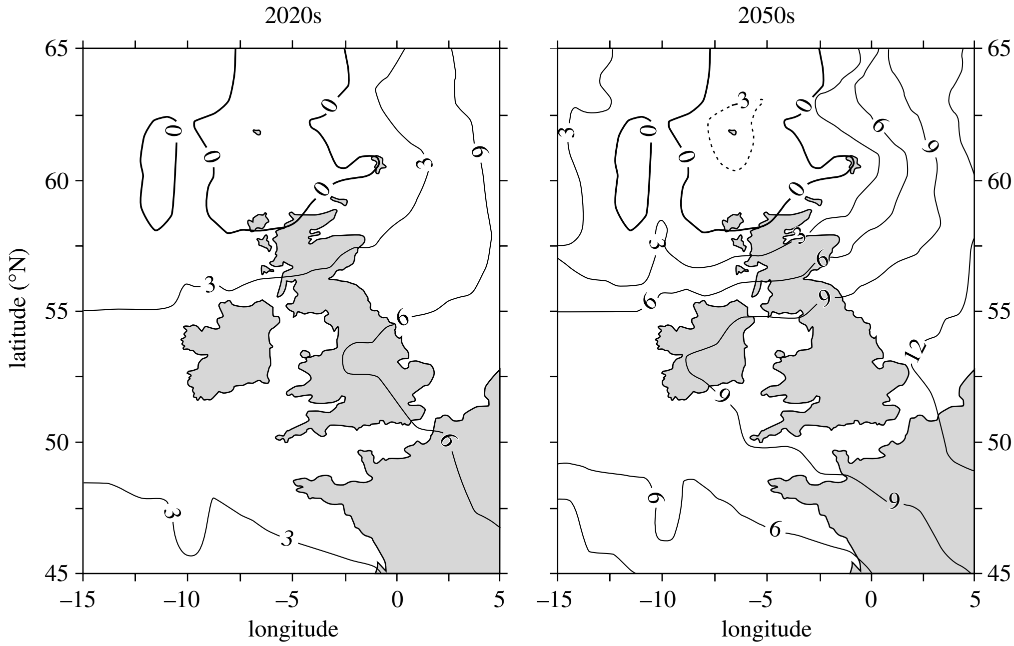

Figure 9. Precipitation trends over the UK expected in a warmer world. The figure shows the percentage change in mean winter precipitation for the 2020s (left) and 2050s (right) decades with respect to the average of 1961–1990. (Figure reproduced courtesy of Climate Change Impacts UK (1996); Crown copyright is reproduced with the permission of the Controller of Her Majesty's Stationery Office).

(*a*) *Forecasting interannual variability*

Interannual climate variability, through its impact on extreme weather events, has arguably a greater impact on industry and our daily lives than multidecadal climate trends. The industries that would benefit from skilful predictions of interannual variability include insurance, power utilities, construction and agriculture. We illustrate current improvements in the long-range prediction of weather and climate extremes by considering landfalling US hurricanes and UK winter storminess.

(i) *US hurricanes*

The *raison d'être* behind long-range US hurricane forecasts is the substantial year-to-year variability present in losses and in the number of hurricanes making landfall. These extremes are typified by the 1997 and 1998 seasons which saw, for the whole Atlantic basin, economic losses of £100 million (1997) and £17 billion (1998). December 1998 saw the release of the first ever long-range forecasts for US landfalling hurricane activity (in 1999). The first was developed by Chris Merchant and myself at the Benfield Greig Hazard Research Centre (BGHRC) of University College London as part of a project for the TSUNAMI consortium of UK insurance companies. It is the first custom built forecast made for (re) insurers. The second forecast comes from the Colorado State University team headed by Bill Gray. The TSUNAMI model uses a mix of dynamical and statistical model predictions of climate parameters for

Figure 10. Royal Leamington Spa, Warwickshire, on Good Friday, 10 April 1998. The town centre is under water and many cars are abandoned in roads. These floods affected a large swathe of central England and caused losses of £350 million. They illustrate a possible impact of global warming. Rainfall and torrential rain will rise, thereby increasing susceptibility to flooding. (Image courtesy of News Team International.)

the coming hurricane season. As the skill of the dynamical model forecasts improves so will the forecasts of hurricane total numbers and landfalling.

It is not possible to compare the performance of the two models for landfalling events, but it is possible for Atlantic total hurricane numbers. Gray and co-workers have been forecasting the latter since December 1991. We show this comparison in figure 11 for events of three different windspeeds: named tropical storms (TC), hurricanes (H), and intense hurricanes (IH). The scatter plots of predicted versus actual numbers suggest the TSUNAMI model is out-performing the Gray model. This is confirmed by comparing the forecast skill of each model using Gray's preferred measure, the 'agreement coefficient' (Gray *et al*. 1992), where a value of 1.0 indicates perfect skill and a value of 0.0 means no skill. For 1992–1998 Gray's model scores −0.04 (TC), 0.04 (H) and 0.02 (IH), while the TSUNAMI model scores 0.20 (TC), 0.25 (H), and 0.30 (IH). For the longer 1984–1998 period the TSUNAMI model scores 0.33 (TC), 0.29 (H) and 0.21 (IH). Other skill measures give similar results. Thus the Gray long-range forecast model has essentially no skill while the TSUNAMI model has skill of order 20–30%.

(ii) *UK storminess*

During the 1990s, UK and European winter storms (see figure 12 for an example) caused economic losses of £1.2 billion per year. As with US hurricanes there is considerable year-to-year variability in numbers and damages.

New research by Steven George and myself of the BGHRC, University College London, shows promise of achieving the first useful long-range prediction of UK storminess. We can predict for southeastern and eastern England, at a lead of six

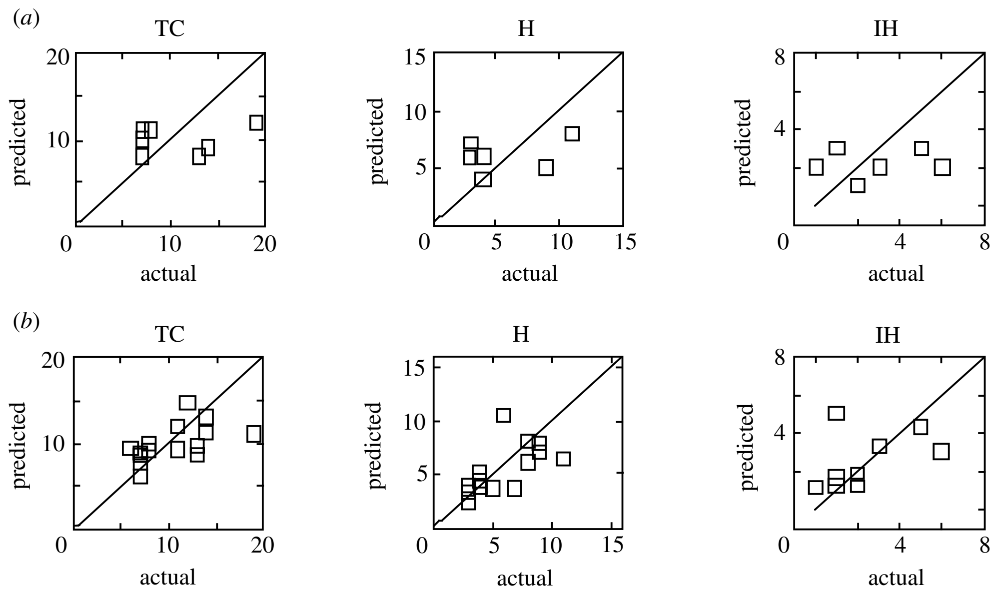

Figure 11. Validation of the Gray (*a*) and TSUNAMI (*b*) December long-range forecasts of Atlantic tropical cyclone and hurricane numbers. The Gray values are forecast values while the TSUNAMI values are hindcasts, i.e. those values which would have been forecast had the model been available. Scatter plots of predicted versus actual numbers are displayed for named storms (TC, maximum sustained wind greater than 17 m s^{-1}), hurricanes (H, maximum sustained wind greater than 33 m s^{-1}) and intense hurricanes (IH, maximum sustained wind greater than 50 m s^{-1}).

months, up to 60% of the year-to-year variability in monthly winter storminess. (Here 'storminess' refers to the mean of the top 5% of six-hourly windspeeds.) This result holds after jack-knifing and other tests of statistical independent skill. Figure 13 compares our hindcast model predictions against observed storminess for February 1959–1997. Three predictors are used based on August data. The strongest predictor, which explains nearly 50% of the year-to-year variance, is a dipole oscillation in sea temperature between the northeast and southeast Pacific Ocean. A climate model is being used to investigate a physical explanation for this link.

(*b*) *Uncertainties beyond 2100*

Projections for climate change beyond 2100 are speculative and subject of course to political decisions on greenhouse gas emissions. However, one can expect that our long-range skill in predicting ENSO and its impacts, landfalling hurricanes, European winter storms, and seasonal extremes in temperature and rainfall, will all improve steadily. Business, industry, and commerce will be able to plan ahead in the knowledge that unexpected climate events are unlikely to impair performance. It is even possible that we will learn how to actively modify and control regional climate to our benefit thereby minimizing the impacts of droughts, floods, windstorms and heat waves.

It is also certain that surprises will happen. Major volcanic eruptions, such as Pinatubo or Krakatoa, will continue to occur giving rise to global impacts on climate lasting a year or two. Based on the past 1000 years, we can expect the Sun's radiation output will continue to vary, probably causing global temperature changes of up to 1 °C during the coming millennium (cf. the Maunder Minimum and Little Ice Age of the 17th century). Should an asteroid or small comet collide with the Earth, as has happened in the recent geological past, the impacts on climate could be even greater.

(*c*) *Major challenges for climate science*

Before the early 1980s there was little scientific and public interest in climate change. The significance of El Niño and its impacts was unappreciated, La Niña was unknown, and the role of the NAO and other teleconnection patterns on interannual climate variability was unrecognized. This situation has now changed completely. Today climate change is constantly in the news, major research programmes are underway to improve climate prediction, and enterprising industries are recognizing the impact of climate and weather on their business performance. Despite these advances, uncertainties abound at almost all levels of climate forecasting. These uncertainties have even led some scientists to question how much of the current warming can be attributed to human activities. Considerable research effort is underway to reduce these uncertainties.

Arguably the greatest challenges now facing climate science are to reduce uncertainties in (1) the effect of aerosols on climate change, (2) the role played by clouds, (3) the effect of climate change on 'flipping systems' such as the North Atlantic circulation pattern called the 'Atlantic Conveyor Belt', and (4) how the frequency and intensity of extreme weather events, especially windstorms, will change in a warmer world.

Aerosols, especially sulphate aerosols, promote climate cooling by reflecting solar radiation back into space (§ 2 *b* (i)). However, calculations for the effect of aerosols on climate change through to 2100 are very uncertain due to several factors. First, scenarios for how sulphur dioxide emissions will change are uncertain. Recent estimates suggest that future emission rates will be lower than envisaged originally. Second, recent models generate a lower sulphate aerosol concentration per tonne of sulphur dioxide emitted. Third, sulphate aerosols can also cool climate by changing the reflectivity and longevity of clouds. This indirect effect now appears as important as the aerosol direct effect but, to date, has not been included in climate models. Fourth, the significance of other types of aerosol such as carbon and soot (which both warm the atmosphere) requires proper assessment.

Clouds can both warm and cool the Earth. They prevent heat from the Earth's surface escaping into space, thereby warming the Earth, and also reflect solar radiation back into space, thereby cooling the Earth. The net effect can be positive or negative depending on the height, temperature and reflecting properties of the clouds, all of which vary in time and from place to place. Our current understanding of the effect of clouds on climate change is poor and they form one of the largest uncertainties.

Few climate systems behave linearly where doubling the input doubles the output. A feature of such complex systems is that small changes in the forcing conditions (i.e. the concentration of greenhouse gases) could lead to abrupt changes or even 'flipping' occurring. Some climate models suggest that the Atlantic Conveyor Belt could be susceptible to this type of disruption if more fresh water entered the Arctic

Figure 12. Satellite image of winter storm Thalia hitting northwest Europe on 21 January 1995. Windspeeds of up to 160 km h^{-1} were recorded. Thalia was the first of four cyclones to bombard the region between 21 January and 2 February 1995. This led to the heaviest rainfall in France in 150 years, 250 000 people being evacuated in The Netherlands, and severe flooding on the Rhine and Mosel. The catastrophe left 37 people dead, and cost £600 million in insured losses and £1.9 billion in economic losses. (Image courtesy of DLR, the German Aerospace Research Establishment.)

Ocean as a result of global warming. Should the Conveyor Belt flip, the Gulf Stream, which is responsible for half of the heat received by the UK and northwest Europe during winter, would move equatorward, leading to a cooler Europe while the rest of the world warmed. The reason for the range of responses in climate models on this issue is not fully understood. However, happily the Conveyor Belt remains steady to date.

If changes in the North Atlantic circulation do occur, the resulting shifts to patterns of sea surface warming and cooling would affect European winter storminess. Even without this complicating factor, the impact of global warming on the frequency and

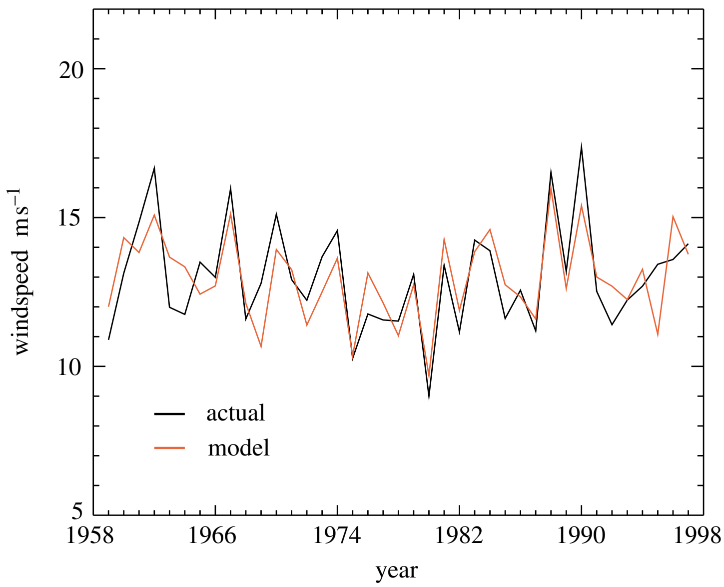

Figure 13. Comparison of model prediction and actual values for top 5% of February storminess in southeastern and eastern England 1959–1997 at 10 m. All model predictions are based on August climate data. The correlation between the two time-series is 0.80 and the model explains 63% of the variance in the observations. (From unpublished work by Steven George and Mark Saunders.)

intensity of extreme weather events, especially hurricanes and windstorms, is the least understood potential impact of climate change. Further research is required on this and on the equally important issue of improved seasonal forecasting of landfalling hurricanes and winter storms.

In conclusion, we are witnessing a unique and exciting era in climate research. The pace of progress and discovery over the past 15–20 years will surely be sustained. As advances continue in computing power and resolution, in the physics of climate models, and in the quality and length of the historical climate record, so will our ability to forecast climate change and its impacts ... this to the benefit of all humankind.

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Born in Tankerton, Kent, Mark Saunders studied at Southampton University where he graduated with first class honours in Geophysical Sciences in 1978. He obtained his PhD in Space Plasma Physics from Imperial College, London, in 1982. He was a European Space Agency Research Fellow at UCLA, and a Royal Society 1983 University Research Fellow at Imperial College, London. He joined University College London in 1993 where he is now Senior Lecturer and Principal Climate Physicist in the Benfield Greig Hazard Research Centre. Dr Saunders leads a group specializing in the long-range prediction of industry-sensitive weather and climate. He is a frequent speaker at conferences and workshops and has published more than 80 scientific research papers and articles. His recreations include running, cricket and golf.