Climate change and its impacts: a global perspective

Some recent results from the UK research programme

Department of the
Environment
Transport
and the Regions

The Met.Office

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Front cover picture
Cloud fractal image by Adrian Pope

Foreword

Human-made climate change poses threats to our world. Global temperatures are already some 0.6 °C higher than they were at the end of the last century, and observations so far this year indicate that 1997 will be one of the warmest years since records began. It is expected that global climate will continue to change throughout the next century, particularly if no additional action is taken to mitigate greenhouse gas emissions.

International action to abate greenhouse gas emissions is focused on the work of the Framework Convention on Climate Change. This Convention draws on the regular assessments of the science by the UNEP/WMO Intergovernmental Panel on Climate Change (IPCC). The last full assessment was completed in 1995, and the next is planned for 2000/1.

As part of the UK's contribution to our understanding of the science, the Department of the Environment, Transport and the Regions (DETR) funds the climate model at the UK Meteorological Office's Hadley Centre, one of the most advanced in the world. The DETR also funds dissemination of the model's output to those scientists able to assess the implied impacts of the predictions.

This booklet describes work being submitted to the IPCC assessment process, in particular the recent results from the Hadley Centre model. However, climate predictions themselves need interpretation to determine the consequential impacts. This brochure therefore goes further and reports the results of a number of impacts studies that have drawn directly on the output of the Hadley Centre using state-of-the-art impact prediction models.

While climate science is still an evolving area of research, it is hoped that this summary will give a sense of our ability to predict possible future climate and to assess its impacts.

Dr David Fisk
Chief Scientist
Department of the Environment, Transport and the Regions

Introduction

Recognizing the threat of future climate change and its impacts, the UK Department of the Environment, Transport and the Regions has established a series of linked research projects which predict changes in climate over future decades and assess the potential global impacts in four key sectors: natural vegetation, water resources, food supply and coastal areas. The best available climate change scenario, using predictions from the Hadley Centre model, has provided a consistent, well-defined basis for quantifying the major impacts in each sector. Contributions to this research from the UK Public Meteorological Service programme are gratefully acknowledged.

Key findings

- The warmest year since the credible global temperature series began in 1860 was 1995. 1997 will be close to this record.
- Analyses of changing patterns of temperature, both at the surface and in the atmosphere, build on the conclusions on attribution in the IPCC 1995 Second Assessment Report, and strengthen the view that human activities have already altered global climate.
- The Hadley Centre model predicts a global warming of about 3° C over the next century, for an emissions scenario close to IPCC 'business as usual'. Inclusion of the cooling effects of sulphate aerosols is expected to reduce this to about 2.5° C.
- By the 2050s, tropical grasslands and forests will be at risk of decline, whereas many temperate and boreal forests may continue to expand in response to climate change and increasing atmospheric CO_2.
- The current ability of vegetation to absorb 20–30% of human-made CO_2 emissions will be maintained initially, but may fall away to zero during the second half of the next century as a result of a decline in tropical vegetation. Consequently, a larger fraction of CO_2 emitted by human activities would remain in the atmosphere thereafter.
- Climate change is likely to exacerbate the pressure put on water resources by an increasing global population, particularly in Africa, Central America, the Indian subcontinent and southern Europe. By the 2050s, the models indicate that there could be about a further 100 million people living in countries with extreme water stress due to climate change alone.
- Global food supply is expected to meet the overall needs of a growing world population but significant regional variations in crop yields due to climate change could lead to increased risk of hunger for an additional 50 million people by the 2080s in the tropics, particularly in Africa.
- Without measures adopted specifically to tackle rising sea levels, increased flooding is calculated to affect some 200 million people worldwide by the 2080s. Around 25% of the world's coastal wetlands could be lost by this time due to sea-level rise alone.

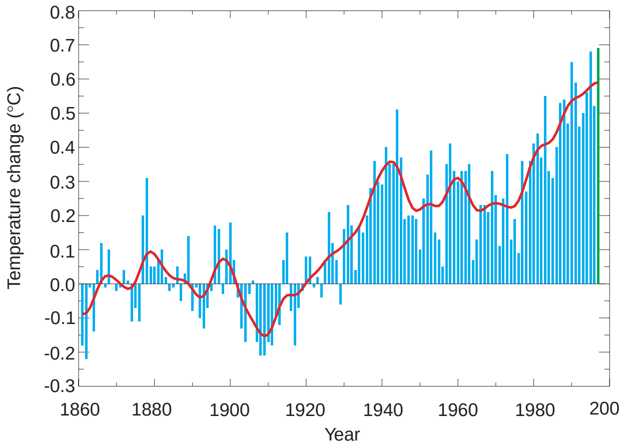
Overall, the results suggest that climate change is likely to intensify the already increasing pressures on various sectors. Although the impact of climate change may, in some cases, be smaller than other stresses on the environment, even relatively small changes can have serious adverse effects, especially where there may be critical thresholds, where development is already marginal, or where a region is less able to implement adaptation measures.

Global assessments can mask important regional differences, and regional impacts have been evaluated here wherever possible. Although some sectors in some regions may experience beneficial effects as a result of climate change, other regions and sectors are likely to face adverse changes. Regions particularly at risk from combined detrimental effects across several sectors are often those least able to adapt.

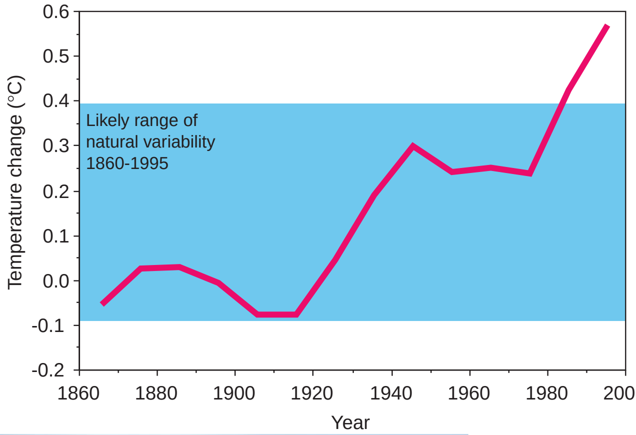
By taking a partially integrated look at how several key sectors will be affected by future climate change, this study has helped quantify some major impacts both on a global and, to a lesser extent, regional scale. It represents a step towards improving the scientific understanding of the impacts of climate change, and highlights both the complex nature of the problem and the urgent need for further research in this area.

Is humankind already changing *global climate*?

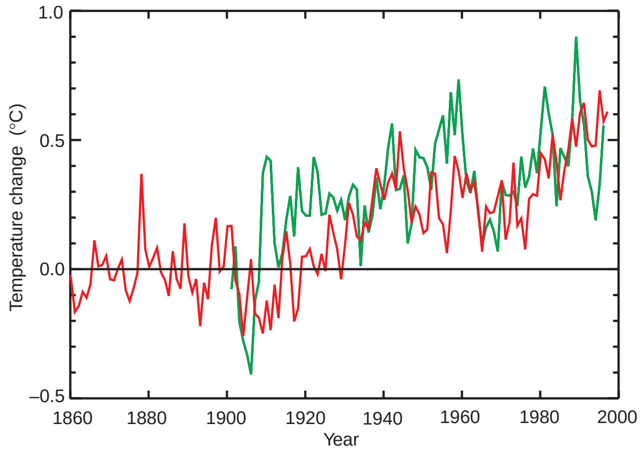
Contributors: Simon Tett, Peter Stott, John Mitchell, Tim Johns, William Ingram, David Sexton, Nick Rayner, Chris Folland, David Parker, Margaret Gordon, David Cullum, Briony Horton, Joe Lavery, Matthew O'Donnell and Geoff Jenkins at the Hadley Centre for Climate Prediction and Research, Meteorological Office.



Surface observations, over land and sea, build up a record of global average annual temperatures since 1860. (The temperature for 1997 (green bar) includes observations up to the end of September.)



The observed change in global mean, decadal-average, temperatures since 1860 is shown by the red line – a decadally averaged version of the previous graph. The shaded area shows the likely maximum range of natural variability of temperatures, as simulated by the climate model.



The change in global mean temperatures since 1900 is simulated by the climate model forced with changes in natural and human-made factors (green), and compared with observations (red).

In its 1995 Second Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) concluded that 'the balance of evidence suggests a discernible human influence on global climate'. Do the results from research in the last two years strengthen or weaken this conclusion? We address this by asking firstly: how is global climate changing? Secondly: are recent changes in climate unusual? And finally: if so, to what extent can they be attributed to human activities, particularly emissions of greenhouse gases?

How is global climate changing?

Change in the global mean temperature of the air at ground level is most often used as a measure of climate change. The Hadley Centre and the University of East Anglia continue to update and refine the global temperature record as a contribution to IPCC, and the top figure shows how the temperature has changed in the almost 140 years since credible global measurements have been maintained. The increase in temperatures has been uneven, but a steady rise over the last two decades has made the 1990s some 0.6 °C warmer than the late 1800s. Nine of the ten warmest years have occurred since 1980; 1995 is the warmest year seen so far, but it seems likely that 1997 will be close to this record. In addition to long-term trends, there are large changes from year to year and decade to decade, largely due to natural interactions between the atmosphere and the oceans, and partly because of other external influences such as volcanic dust and changes in the sun's output.

Is the recent change unusual?

To answer this question, we would like to compare the observed temperature trend over the 137-year period 1860 to 1996 with that due to natural variability in similar periods over, say, the past thousand years. However, because measurements are not available, we use the Hadley Centre second-generation coupled atmosphere–ocean climate model to simulate a thousand years of global climate and take the maximum range of variability in any 137-year period in the simulated record. Changes in solar output and volcanic dust will also cause climate to change naturally; estimates of the temperature changes due to these factors since the middle of the last century are also given by the model. The blue shaded area in the middle figure shows the estimated likely maximum range of temperature change due to both internal climate processes and solar and volcanic changes, compared with recent observations. It can be clearly seen that, if the model adequately simulates the natural variability of the real climate (and the evidence we have leads us to believe that this is the case), then the past couple of decades have indeed been unusually warm.

Has human activity played a part in this change?

Just because the recent temperature change is unusual, it does not necessarily mean that human activities are the cause. We have to show that the changes seen are similar to those predicted to arise from human activities, and different from those which might have occurred naturally. We have run the Hadley Centre climate model with factors, both natural and human, which will have influenced climate since 1860: natural variability (which is inherent in the model), changes in solar output and volcanoes, and human-induced changes in the concentrations of greenhouse gases (including ozone) and sulphate aerosols. The change in global temperatures simulated by the climate model is in broad agreement with those actually observed (see bottom figure on opposite page). This implies that we are beginning to understand the reasons (including human influences) for temperature changes over the last 140 years, but does not exclude the possibility that this agreement is partly fortuitous.

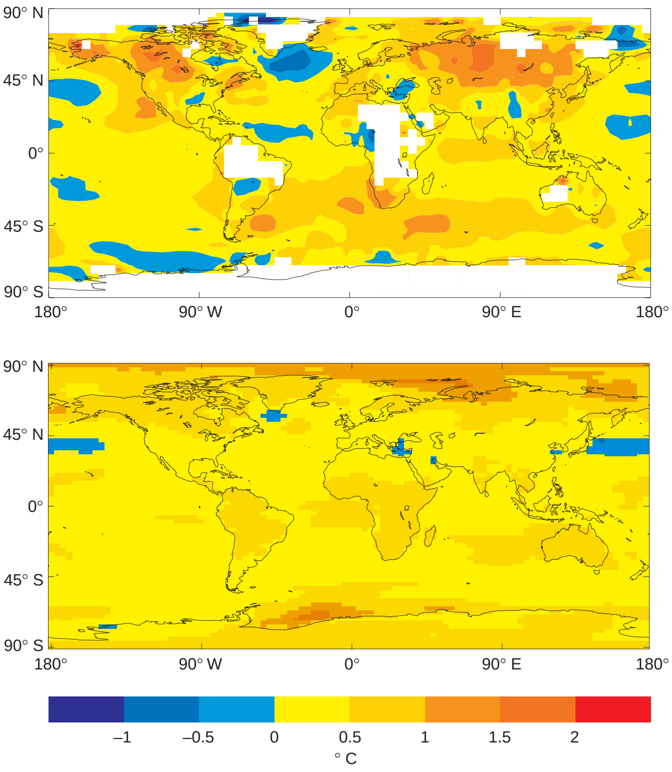
Some of the human influences, such as aerosols, have strong effects on regional climate. So, in addition to looking at global averages, we look at the patterns of change in temperature across the globe, which are more sensitive to the specific causes of change. The climate model is used to generate a fingerprint of change across the globe due to human activities between the turn of the century and the 1990s; this is shown right in the two top figures, together with the corresponding observed pattern of change. Some similarities can be seen by eye. Statistical tests show that the predicted fingerprint of change expected from human activities can be seen in recent decades, but is absent in earlier years.

Weather balloons give us a record of temperature changes over the past few decades through the depth of the atmosphere. These observations are also compared with the climate model's simulations over the same period in the bottom two figures; the human-made increase in atmospheric greenhouse gases is the only known mechanism which can explain the observed long-term lower atmospheric warming and stratospheric cooling.

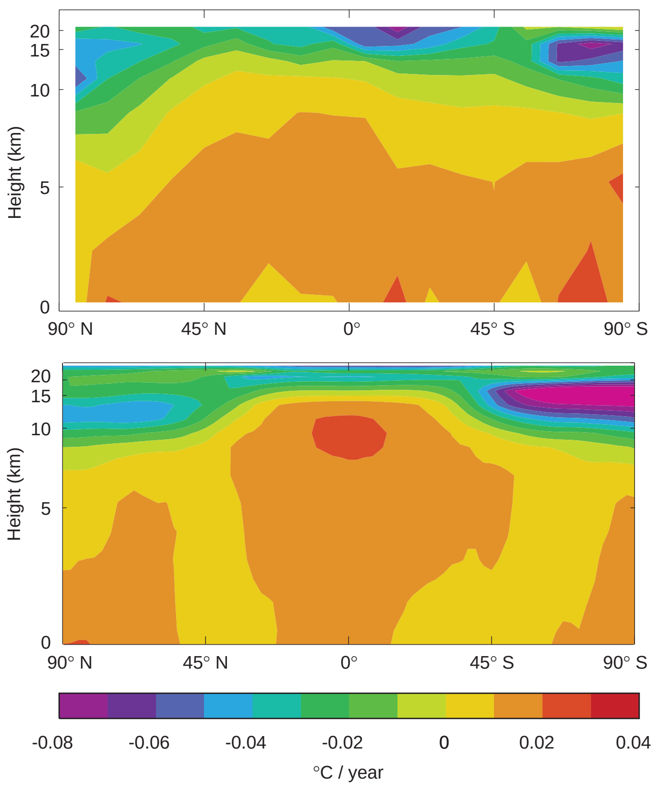
Global temperature is continuing to increase, and has recently risen beyond the estimated range of natural variability. This new research, following on from IPCC 1995, gives us increasing confidence that human activities have contributed, at least in part, to the global temperature rise over recent decades.

Conclusions

- The warmest year since credible global averages started in 1860 was 1995; 1997 will be close to this record.
- The temperature rise over the last decade or so has been outside the range of natural variability simulated by the Hadley Centre climate model.
- When driven by observed changes in human-made and natural influences, the model simulation of global mean surface temperature is in broad agreement with observations
- Observed patterns of temperature change, both across the surface of the earth and through the depth of the atmosphere, can be explained by including the influence of human activities, particularly emissions of greenhouse gases and sulphur.



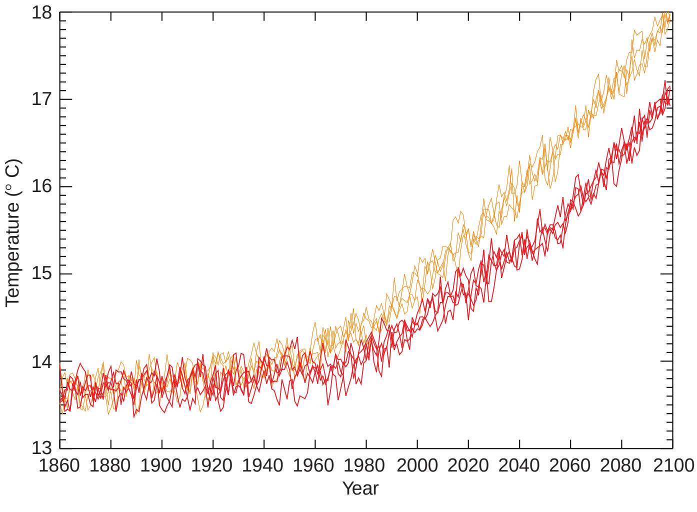
The pattern of changing temperatures, between the present day and the turn of the century, across the surface of the earth: bottom, as simulated by the climate model; top, as observed. Certain similarities, for example the greater warming at higher latitudes, can be seen by eye, and this correlation can be demonstrated more rigorously using statistical techniques.



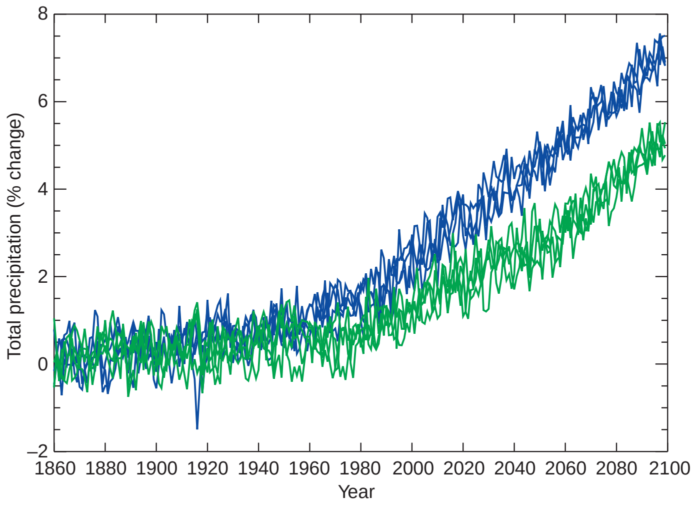
Temperature trends from 1961 to 1996 through the depth of the atmosphere: bottom, as simulated by the climate model; top, as observed. The long-term cooling stratosphere and warming troposphere can only be explained by human influence.

How much more will *climate change* in the future?

Contributors: John Mitchell, Tim Johns, Jonathan Gregory, Matthew Eagles and Geoff Jenkins, Hadley Centre for Climate Prediction and Research, Meteorological Office; Scenarios: David Viner, Mike Hulme, Phil Jones, Mark New and Elaine Barrow at the Climatic Research Unit of the University of East Anglia.



Ensembles of four predictions of global mean temperature resulting from 'business as usual' changes in greenhouse gases following on from observed changes since 1860 (orange curves). The addition of sulphate aerosol cooling is shown in the red curves.



As above, but for precipitation (rainfall and snowfall). Changes with (green) and without (blue) the effects of sulphate aerosol.

Modelling climate change

The basis of predictions of future climate change (and simulations of past climate change) is the climate model; a mathematical representation of the climate system which can be used to explore the effect of changes in factors such as greenhouse gases, small aerosol particles from human-made and volcanic sources, and solar output. In addition to these external factors, climate varies from year to year and decade to decade of its own accord, largely due to interactions between ocean and atmosphere, and this internal variability is also represented in the climate model.

Climate models have been criticized for their use of artificial corrections ('flux adjustments') in order to prevent the model climate drifting away with time from an adequate representation of observed climate. However, early results from the new Hadley Centre model, which has been developed to avoid the use of such adjustments, show global mean changes which are very similar to those presented in this brochure; the use of adjustments does not appear to invalidate predictions.

We are gaining confidence that the results from climate models do broadly represent the way in which climate will change over future decades on a global and continental scale. But detailed impacts assessments demand information at a regional and national scale, and predictions of not just mean changes, but changes in the variability and extremes of climate. The provision of this level of detail still presents climate researchers with a considerable challenge.

Confidence in predictions from climate models is limited by an imperfect understanding of processes which control climate; the real world may respond to increasing greenhouse gases in a very different way to the climate model. For example, it has been suggested that the intense deep-water currents which are responsible for redistributing heat between the equator and the poles could decrease or even switch off as a consequence of increasing greenhouse gas concentrations. Recent research elsewhere has also indicated that the severity of change in these currents could depend crucially on the rate of build-up of greenhouse gases.

Future climates

Future changes in climate are explored by driving the climate model, firstly with observed changes (for example that due to increasing atmospheric carbon dioxide) from 1860–1995, followed by a projected increase in concentrations of greenhouse gases. At the Hadley Centre, we made four model runs of the same experiment where greenhouse gases increase at approximately the IPCC IS92a ('business as usual') rate. Each run started from slightly different initial conditions which span a range of natural variability, to make an ensemble of predictions. From this, we can show (see figure top left) that the underlying longer-term climate prediction from each run is the same (just over 3 °C global temperature rise from the present day to the end of the next century) and is not sensitive to the starting conditions.

A smaller global temperature rise, of about 2.5 °C, is predicted when the cooling effect of aerosols is included. Changes in precipitation (rainfall and snowfall) are also shown in the bottom figure.

In the past, impacts studies have been compromised by the large random natural variability associated with a single model prediction. By taking the simple average of the individual members of the ensemble of runs, we can reduce this noise and hence improve the representativeness of climate scenarios used for impacts assessments. The figures alongside show the ensemble-mean changes in temperature and precipitation expected for the period 2041–2070, relative to current climate.

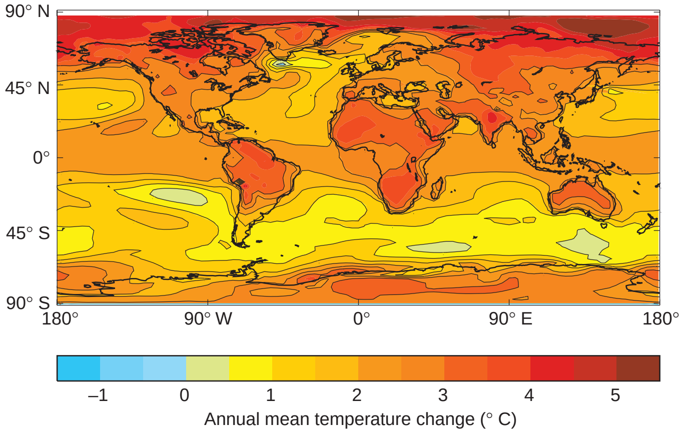
Climate predictions which account for the cooling effects of sulphate aerosols generated from emissions of sulphur dioxide from human activities, were made for the first time by the Hadley Centre in 1995. As shown opposite in the top figure, the global mean changes in temperature by 2100, relative to pre-industrial times, are smaller by about a degree than those when sulphate particles are neglected. Areas of less warming are more marked near and downwind of industrial regions. However, the effective lifetime of sulphate aerosols in the atmosphere is only a few days, compared to about 100 years for carbon dioxide. Thus any decrease in sulphur emissions will remove the cooling effect and warm the earth relatively rapidly in the short term; in this sense, sulphate aerosols only temporarily mask the effect of human-made greenhouse gas emissions. In addition, there are great uncertainties about future emissions of sulphur, its conversion to particles and their climate impact.

Scenarios of change

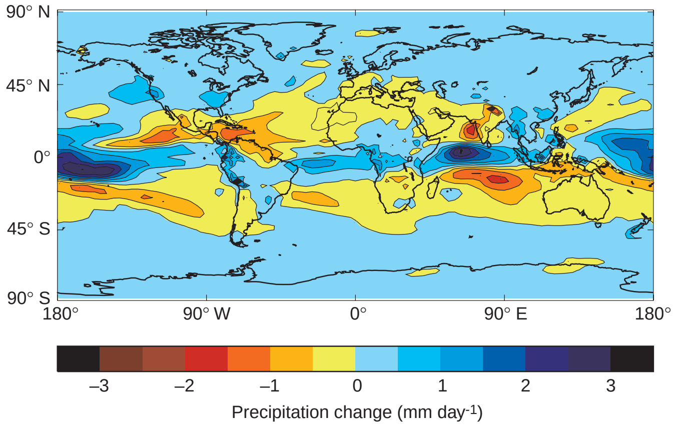
Scenarios of climate change are derived from the Hadley Centre predictions, without the effects of sulphate aerosols, for reasons given above.

In addition, the impacts assessments in this report use common assumptions for other factors. The baseline climate for 1961–90 is that recently developed by the University of East Anglia. Future CO_2 concentrations are estimated using a standard IPCC emissions scenario, consistent with the forcing used by the Hadley Centre model. The World Bank 1994/5 scenario is used for projections of population, and economic growth is taken from the Energy Modelling Forum 14 scenario. Impacts calculated using these assumptions but without any change in climate are termed reference scenarios.

Assessments have been made using mean monthly changes in three future 30-year time periods centred on the 2020s, the 2050s and the 2080s, taking a simple average of the four members of the ensemble of model predictions.



The change in annual temperatures for the 2050s compared with the present day, when the climate model is driven with an increase in greenhouse gas concentrations equivalent to about a 1% increase per year in CO_2. The picture shows the average of four model runs with different starting conditions. Higher latitudes will warm faster than lower latitudes due to the feedback effect of sea-ice melt. Land areas will warm faster than the ocean.



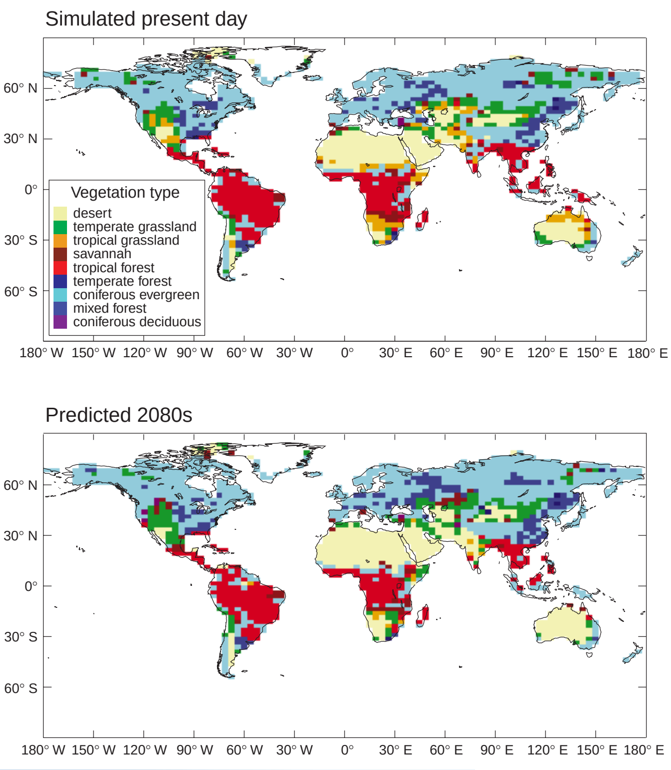
As above, but showing the change in annual precipitation for the 2050s compared with the present day. There is enormous regional variability in these changes, with large areas of both increased and decreased precipitation (rainfall and snowfall).

Common assumptions for the impacts assessments

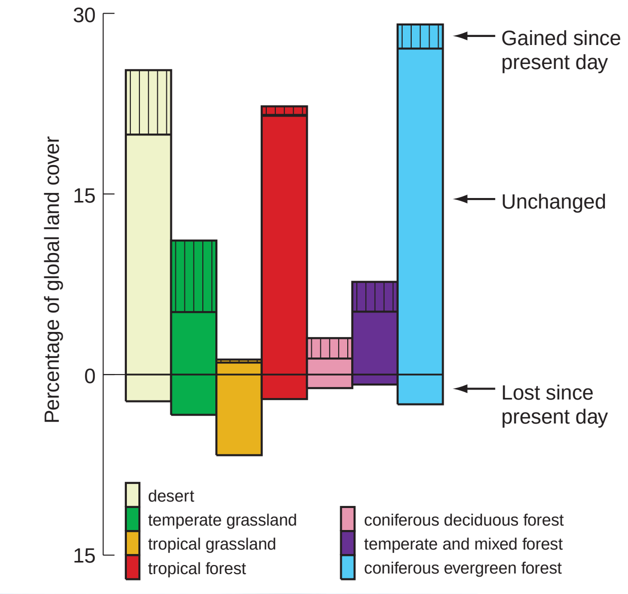
	Present day	*2020s*	*2050s*	*2080s*
CO_2 concentration (ppm)	365	441	565	731
Temperature change (°C)	0	1.2	2.1	3.2
(including sulphate aerosol)	0	1.0	1.6	2.6
Precipitation change (%)	0	1.6	2.9	4.5
Sea-level rise (cm)	0	10	26	44
Population (millions)	5,266	8,121	9,759	10,672

The impact of *climate change* on natural vegetation

Contributors: Andrew White, Andrew Friend and Melvin Cannell, NERC Institute of Terrestrial Ecology, Edinburgh.



Global distribution of vegetation types predicted by an ecosystem model for the present day and the 2080s. Note the increase in mixed forest and the reduction in tropical grassland and forest.



Simulated global vegetation for the present day and the 2080s expressed as a percentage of the global land area. Vegetation is shown divided into six categories (combining temperate and mixed forests, and assigning savannah to forest and grassland categories). The areas gained, unchanged and lost between the present day and the 2080s are distinguished.

The type of vegetation that grows naturally in any region of the earth, and the amount of carbon that is stored in that vegetation and associated soils, can be predicted from the climate using ecosystem models. The Hybrid model, which has been well-tested and peer-reviewed, is used to simulate the global distribution of natural vegetation and carbon as it exists now and how it may change in response to gradually changing climate, increasing atmospheric CO_2 and nitrogen deposition from the atmosphere. The responses to a gradually changing climate reported here differ from those in the IPCC Second Assessment Report, which only considered responses in a world that had come to a new equilibrium temperature. The model simulates the cycles of carbon (energy), nitrogen and water. Eight possible vegetation types are modelled — temperate grassland, tropical grassland, savannah, tropical forest, temperate forest, coniferous evergreen forest, mixed forest and coniferous deciduous forest. Areas that cannot support any of these vegetation types are classed as 'deserts'. The type of vegetation which dominates at any location depends on the outcome of competition for light, nitrogen and water and the ability of the plants to survive extreme conditions. The model describes the potential natural vegetation that would exist without interference by humans, such as the recent rainforest fires.

Changes in the potential distribution of natural vegetation

The maps (above left) show the global distribution of desert and the eight vegetation types as predicted for the present day and the 2080s. The figure below shows changes over that period in the percentage of the global land area which is covered by desert and six vegetation types (combining temperate and mixed forests, and assigning savannah to forest and grassland categories). Similar patterns of change, although less extreme, are seen for the 2020s and the 2050s.

The majority of regions where tropical grasslands currently dominate are predicted to change to temperate grassland or desert by the 2080s; in fact, tropical grasslands will shrink from 8% to 1% of the global land area. Some regions which currently support different types of tropical forest will change to savannah, grassland or even desert — without human interference. The model predicts that this tropical 'dieback' will begin in the 2050s as a result of decreases in rainfall and increases in mean annual temperature, which may be as large as 5–8 °C in parts of northern South America, the Sahel and India. In general, all tropical vegetation types are at risk. As a consequence there is likely to be a major loss in global biodiversity.

By contrast, there is predicted to be a net expansion in areas of temperate and mixed forest in both North America and Asia and little overall change in the vast areas of northern coniferous forest. In addition, these forests will grow faster as a result of more favourable temperatures, adequate rainfall and nitrogen deposition from the atmosphere. Results suggest that the potential biomass between latitudes 30° N and 60° N will increase by 70% between the present day and the 2080s.

Changes in the carbon sink on land

At present, only about half of the CO_2 emitted to the atmosphere by human activities remains there as a greenhouse gas. Much is taken up by the oceans and, in order to balance the global carbon budget, the remaining 1–2 Gigatonnes of carbon (Gt C) per year is assumed to be added to the store of organic matter in vegetation and soils on land. This terrestrial sink of 1–2 Gt C per year exists if the rate at which organic matter is produced by photosynthesis exceeds the rate at which it decomposes back to CO_2, therefore the net ecosystem productivity of the world is 1–2 Gt C per year. This assumption may be correct, because increasing atmospheric CO_2 concentrations and nitrogen deposition are probably accelerating global rates of photosynthesis. The important consequence is that a carbon sink may exist on land which is acting as a 'brake' on the rate at which the CO_2 concentration is increasing in the atmosphere, so reducing the radiative forcing.

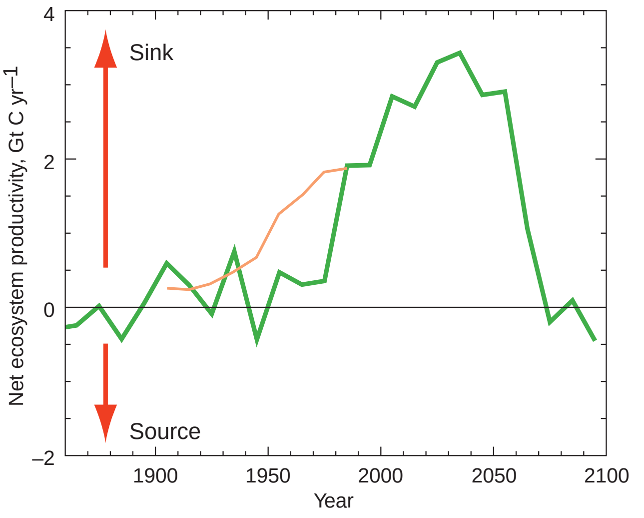
The main reasons for the increase in the terrestrial carbon sink in the first half of the next century are increases in the biomass of tropical forests, and in both area and biomass of the northern temperate and boreal forests. The main reasons for the collapse of the global terrestrial carbon sink are the loss of tropical forests as a result of climate change, and a weakening of the CO_2 and nitrogen fertilization of photosynthesis and growth.

The ecosystem model was also used to predict the amount of carbon stored in global vegetation and soils from 1860 to 2100 in response to climate change, increasing atmospheric CO_2 and nitrogen deposition. The change in the terrestrial carbon store — the carbon sink (or source) on land — is expressed as global net ecosystem productivity in the figure (top right). The next figure (bottom right) then shows the fraction of the carbon emitted by human activities that is taken up by this terrestrial sink.

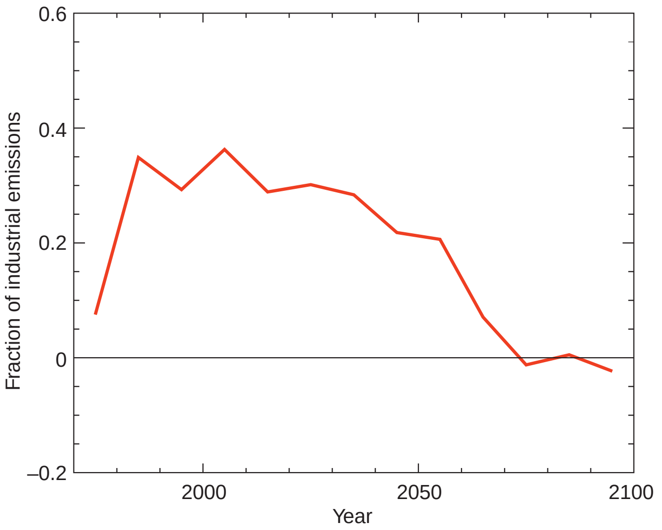
The model predicts that the carbon sink on land increased in recent decades, as also predicted by atmosphere–ocean models of the global carbon budget. There is agreement that the current terrestrial carbon sink is 1–2 Gt C per year taking up about 20–30% of the carbon emitted by human activities. Results suggest that this sink will increase to about 3 Gt C per year or more by 2050, continuing to absorb at least 20% of the carbon emitted by humankind. But after about 2050, the terrestrial sink dramatically decreases and disappears by about 2080. Consequently, more of the CO_2 emitted by human activities will then remain in the atmosphere.

Conclusions

- By the 2080s, many tropical grasslands and tropical forests will be at risk of decline and loss in biomass and areal extent, whereas many temperate and boreal forests may continue to grow faster and increase in areal extent in response to climate change.
- The terrestrial carbon sink may continue to provide a substantial 'brake' on the rate of increase in atmospheric CO_2 until about 2070, but thereafter it is likely that this sink will disappear as tropical forests are adversely affected by climate change.



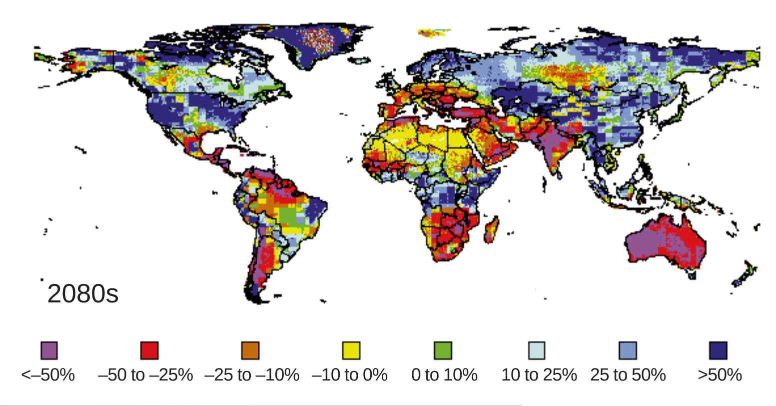
Predicted effects of changes in climate and atmospheric CO_2 on global net ecosystem productivity (i.e. the rate of increase in the terrestrial carbon store) showing when the land surface is a sink or source of carbon. Also shown is the estimated carbon sink (red) required to balance the global carbon budget in atmosphere–ocean models, 1900–1990.



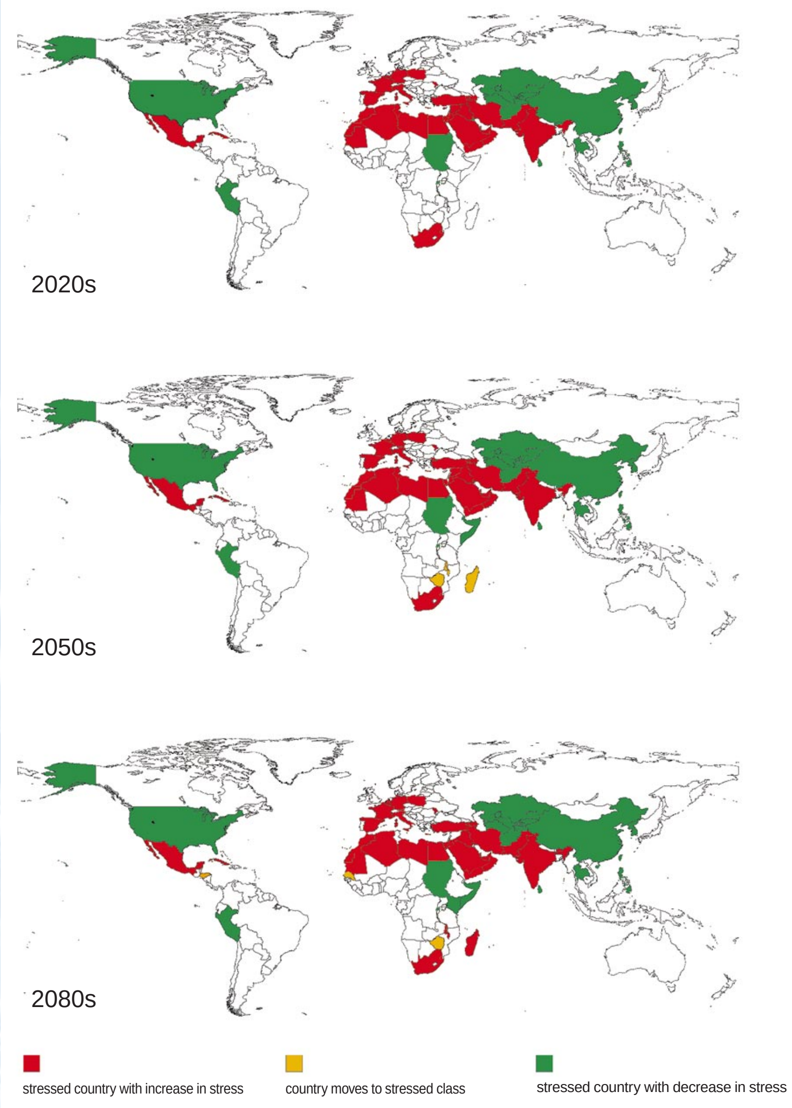
The data in the figure above is expressed as a fraction of the projected anthropogenic carbon (CO_2) emissions – the fraction of emissions resulting from human activities that is predicted to be taken up by the terrestrial carbon sink.

The impact of *climate change* on water resources

***Contributors:* Nigel Arnell and Rebecca King,**
University of Southampton.



Percentage change in 30-year average annual runoff by the 2080s.



Change in water stress, due to climate change, in countries using more than 20% of their potential water resources.

Climate change will affect the water balance, and particularly the amount of runoff and recharge, which in turn determines the water resources available for human and ecosystem uses. Some parts of the world will experience a reduction in resource availability, while others will see an increase. Here we assess the effects of climate change on water resources both globally and regionally, comparing these effects with other stresses on the environment.

Interest in global water resources has risen significantly in recent years, largely as increasing populations and the concentration of population within urban areas have increased pressures on the amount and quality of water resources. The Comprehensive Assessment of the Freshwater Resources of the World estimated in 1997 that approximately one third of the world's population lives in countries experiencing moderate to high water stress, and forecast that by 2025 as much as two thirds of a much larger world population could be under stress conditions simply due to the rise in population.

Indices of water resources

There are many possible indices of water stress, considering different aspects of use and availability. The basic measure used in the Comprehensive Assessment is the ratio of the amount of withdrawals to the renewable resources available in a country, including runoff imported from upstream regions. For comparative purposes, the current study used the same indices. In the absence of consistent data at more local scales, the indices are calculated using national population and water resource statistics. Baseline estimates of current national water resources, both generated internally and imported from upstream, were taken from data prepared for the Comprehensive Assessment, as were figures for current withdrawals.

Future withdrawals of water will increase with population. This study, like the Comprehensive Assessment, assumes that the per capita use will remain constant over the next few decades. This is perhaps unrealistic, because in practice use would change as economic development changes, water use efficiency increases and if irrigation use increases at a different rate to population. Climate change might also have an effect on the demand for water.

It is generally accepted that water resources become a constraint on development when use exceeds 20% of the total resources potentially available. Such countries are prone to severe problems during drought years, and without action to provide secure supplies (through investment in supply facilities) development opportunities are constrained. Countries using less than 20% of total potential resources are not immune to water stress, and may experience very severe problems in some regions and at some times.

Estimating changes in runoff and water resources

The amount of water notionally available for use comprises runoff in rivers and recharge to groundwater. A macroscale daily hydrological model, with a spatial resolution of 0.5° × 0.5°, was used to simulate runoff given changes in precipitation, temperature and potential evaporation derived from the climate model simulations. When used with current climate data, the broad geographic distribution of runoff was well simulated. Estimates of national runoff were derived by overlaying the model's 0.5° × 0.5° grid with national boundaries. Percentage changes in national runoff under the climate change scenarios were then applied to the observed national runoff data to determine the volume of resources available under the climate change scenarios.

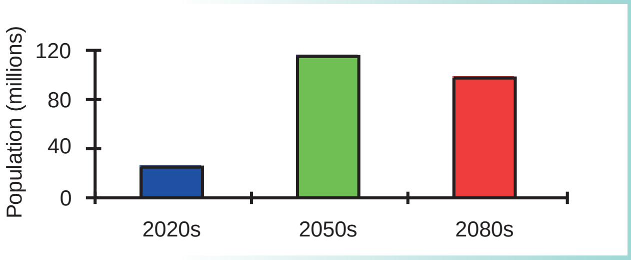
Changes in runoff

Under the future climate change scenario, runoff generally increases in high latitudes and the equatorial region, and decreases in middle latitudes. The increase in total global runoff is 2.9% by the 2020s, 4% by the 2050s and 6.5% by the 2080s, and the broad pattern of change is consistent from one time period to another. The top map opposite shows the percentage change in average annual runoff by the 2080s. Some parts of the world, most notably southern Africa, large parts of the Indian subcontinent, northern South America, central America and Europe, experience substantial reductions in runoff and hence water resources. In other populous regions, however, such as South East Asia, annual runoff is projected to increase substantially.

Climate change will alter not only the amount of water in rivers, but also the timing of flows through the year. Areas with snowfall will be particularly affected, as higher temperatures will mean less precipitation falls as snow. In many regions, such as northern and eastern Europe and large parts of North America, the present spring snow peak will be considerably reduced and an increasing proportion of flows will occur during winter.

Changes in water resources

In 1990, approximately 1.9 billion people lived in countries using more than 20% of their potential resources. With population increase alone, this figure would rise to 5.1 billion by 2025, 5.9 billion by 2055 and 6.5 billion by 2085. The three lower maps opposite show the effect of climate change on these stressed countries in the 2020s, 2050s and 2080s. In some countries — notably China and the United States — climate change will lessen national-scale water resource stresses. In many other countries, however, climate change will increase stresses. North Africa, southern Africa, the Middle East, the Indian subcontinent, central America and large parts of Europe will be adversely affected by climate change by the 2020s. By the 2050s, a few more countries in southern Africa will move into the stressed class due to climate change.



Change, due to climate change, in the number of people living in countries with extreme water stress.

An increasing proportion of the world's population will live in countries with extreme water stress, using more than 40% of their available resources: estimated totals are 454 million people in 1990, 2.4 billion in 2025, 3.1 billion in 2050 and 3.6 billion by 2085. The figure above shows the increase in population under extreme water stress due to climate change. The increase is slightly smaller in the 2080s because of the differential population growth rates.

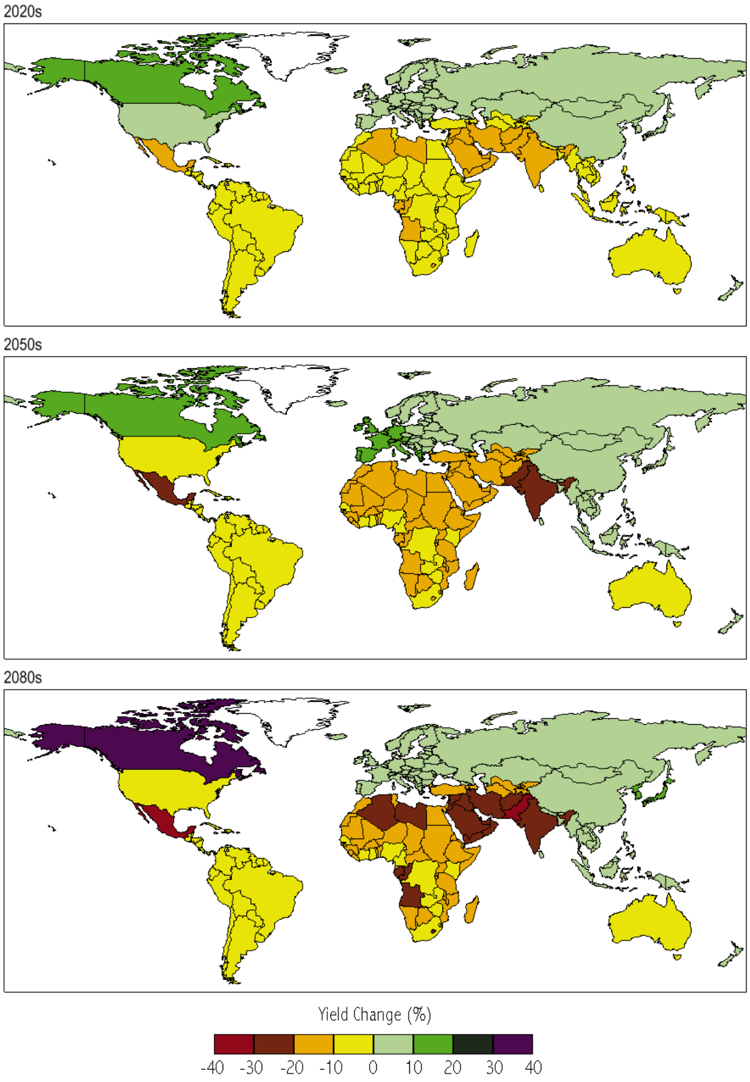
Conclusions

- Climate change will increase the total amount of runoff, but this increase will not be evenly distributed worldwide. Mid-latitude regions will experience reductions in river flows.
- Climate change will also alter the timing of streamflow through the year, particularly where snowfall is reduced or eliminated.
- Population growth is putting increasing strain on the available water resources. Stresses in a number of countries — particularly in Africa, the Middle East and the Indian subcontinent — are likely to be exacerbated due to climate change. Pressures in some countries will be eased.
- By the 2050s, the study suggests that there could be another 100 million people living in countries with extreme water stress due to climate change alone.

The impact of *climate change* on food supply

***Contributors:** Martin Parry, Jackson Environment Institute, University College London; Cynthia Rosenzweig, Goddard Institute for Space Studies, USA; Ana Iglesias, Cuidad Universitaria, Spain; Günther Fischer, International Institute for Applied Systems Analysis, Austria; with Matt Livermore, Jackson Environment Institute, University College London.*

Validated dynamic crop growth models are used to simulate the effects of climate change and increased atmospheric CO_2 on the yield of major crops. An established world food trade model is then used to simulate the economic consequences of climate and CO_2-induced changes in yields and thus estimate the changes in world food output, in world food prices and in the number of people at risk from hunger. All models and methods used in this analysis have been peer-reviewed in leading international science journals, but this is the first occasion in which they have been used to analyse effects under a transient climate change scenario.



Percentage change in average crop yields for the climate change scenario. Effects of CO_2 are taken into account. Crops modelled are: wheat, maize and rice. Changes shown are averaged for national or regional levels based on the economic components of the Basic Linked System.

Crop yield changes

Estimated changes in national grain crop yields were made based on simulations using IBSNAT/ICASA crop models and the climate change scenarios at 82 sites. Maps of average projected crop yields are shown left for the 2020s, 2050s, and 2080s. The pattern of yield changes follows for the most part that of earlier studies reported in the IPCC Second Assessment Report, i.e. positive changes in the mid and high latitudes and negative yield changes in the lower latitudes. Strong regional differences are seen in these results. For example, the Indian subcontinent and the Middle East suffer simulated yield losses while Canada, Japan, the European Union, and New Zealand experience yield gains. Crop yields in some regions may initially increase then decrease through the decades, due to the changing balance between positive effects of CO_2 fertilization and the negative effects of temperature stress. This clearly has implications for adaptation policies.

World food output

The world food model (the Basic Linked System) incorporates climate responses as changes in average national or regional yield per commodity as described above. Economic adjustments include changes in agricultural investment, allocation of land to different crops, land reclamation and prices. A 'risk of hunger' index is based upon methods developed by the UN Food and Agricultural Organization (FAO).

Under standard assumptions about the future and assuming no change in climate, world cereal production is estimated to grow from about 1,800 million metric tonnes (mmt) in 1990 to about 3,500 mmt in 2050, matching global food requirements throughout the period. Food prices are estimated to rise but the relative risk of hunger will decrease. These projections are consistent with those of FAO. They assume a 50% liberalization of trade by 2020 and an annual increase in cereal yields of just under 1%. Some consider these assumptions to be optimistic, but they are consensus best estimates.

Climate change due to greenhouse gases alone (without the effects of sulphate aerosols) will cause world cereal production to be progressively reduced: by about 15 mmt in the 2020s, 60 mmt in the 2050s and 105 mmt (or 2%) in the 2080s (top figure, right). While these amounts do not appear to be large, they imply significant effects on global food prices and the risk of hunger. Food prices increase by 5% in the 2050s and by around 10% in the 2080s above the level they otherwise would have been (second figure). The number of people at risk of hunger (middle figure) is projected to be about 36 million more by the 2020s (above the level otherwise expected).

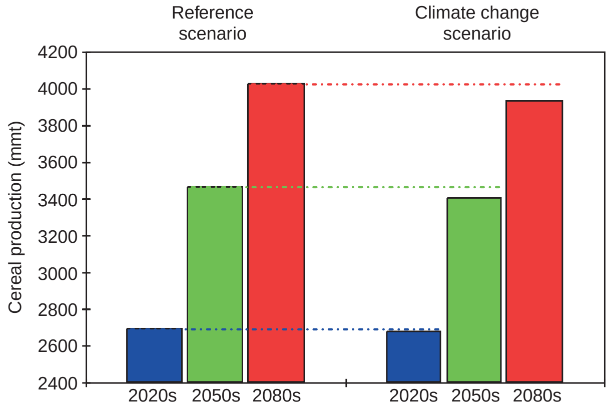
Regional effects

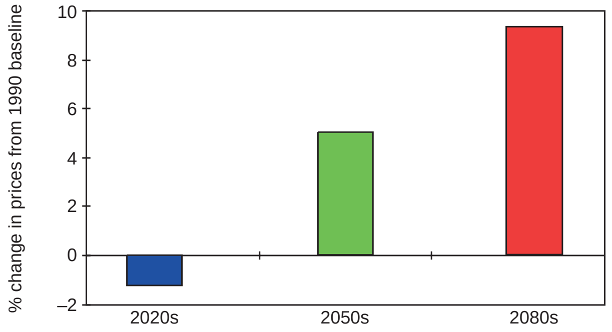
The global estimates presented above mask important regional differences in impacts. In general, yield increases at high and mid-latitudes lead to production increases in these regions, a trend that may be enhanced due to the greater adaptive capacity of countries here. Both Canada and Europe are good examples of this. In contrast, yield decreases at lower latitudes, and in particular in the arid and sub-humid tropics, lead to production decreases and increases in the risk of hunger, effects that may be exacerbated where adaptive capacity is lower than the global average. For example, in Africa, cereal productivity is estimated to be reduced by about 10% from the reference case by 2080, and the consequent risk of hunger would increase by one fifth (bottom two figures).

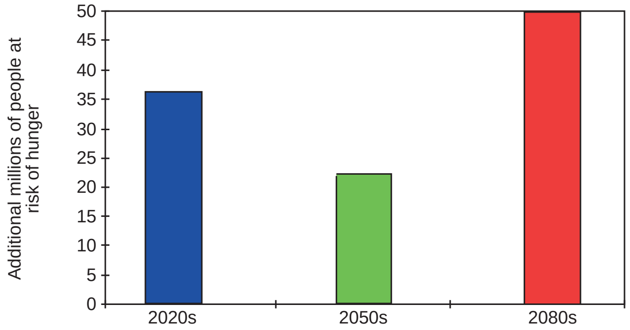
Conclusions

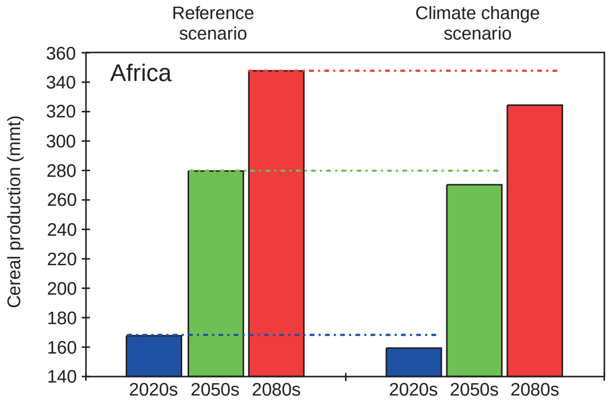
- Transient climate change is expected to increase yields at high and mid-latitudes, and lead to decreases at lower latitudes, this pattern becoming more pronounced as time progresses. This confirms results reported previously for analyses with 2 × CO_2 climate change scenarios.
- The food system may be expected to accommodate such regional variations at the global level, with production, prices and the risk of hunger being relatively unaffected.
- However, some regions (particularly the arid and sub-humid tropics) will be adversely affected, experiencing marked reductions in yield, decreases in production and increases in the risk of hunger.

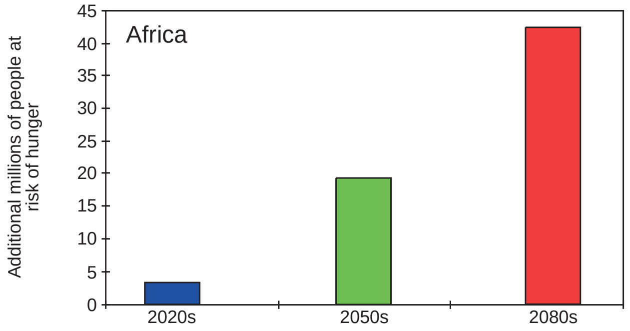
Finally, this is a global and long-term assessment, focusing on average effects over space and time. At the local level (e.g. in especially vulnerable areas) and over short periods (e.g. in spells of drought or flooding) many of the effects of climate change will be more adverse, as indicated in the IPCC Second Assessment Report.











Figures, top to bottom:

Projected global cereal production for reference case and the climate change scenario.

Percentage change in global cereal prices under the climate change scenario (0 = Projected reference case).

Additional people at risk of hunger under the climate change scenario (0 = Projected reference case).

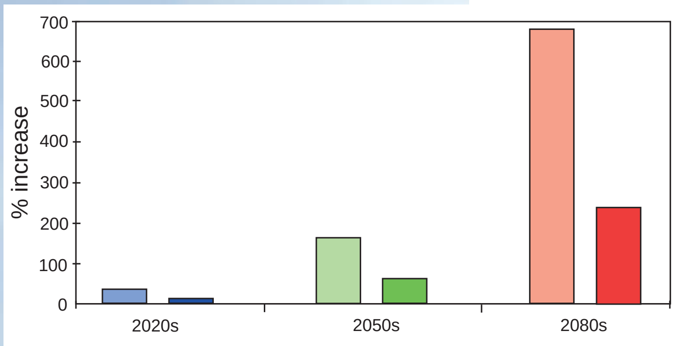
Projections for cereal production in Africa under the reference case and the climate change scenario.

Additional number of people at risk of hunger in Africa under the climate change scenario (0 = Projected reference case).

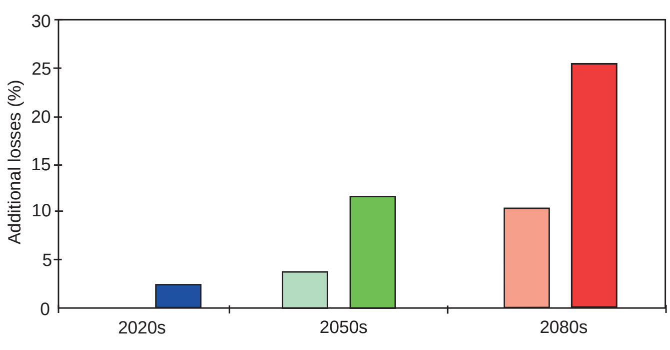
The impacts of *sea-level rise* on coastal areas

Contributors: Robert Nicholls, Middlesex University, London;
Frank Hoozemans and Marcel Marchand, Delft Hydraulics, Netherlands.

The 1995 IPCC Second Assessment Report estimated changes in the number of people flooded by storm surges due to a one metre sea-level rise, and the losses in coastal wetlands. The rise in sea level assumed was just above the top end of the range for 2100 suggested by IPCC, and the calculations did not consider the rapid socio-economic changes which are occurring in the coastal zone. To estimate the impacts of sea-level rise on coastal flooding and coastal ecosystems more realistically, we consider the effects of three simultaneously changing factors: global sea-level rise, coastal population, and upgrading flood protection due to increasing national wealth. It should be noted that storm surge climatology is assumed to be constant. If the number of coastal storms increased, the impacts of flooding would be exacerbated and vice versa.



Percentage change in the number of people at risk under the sea-level rise scenario and constant (1990s) protection (left bar) and the sea-level rise scenario and evolving protection (right bar).

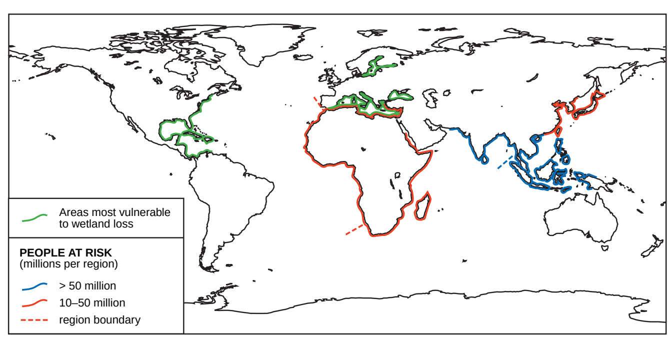


Percentage additional losses of coastal wetlands due to the sea-level rise scenario assuming low-loss (left bar) and high-loss (right bar) scenarios.

Coastal flooding

To estimate the number of people affected by flooding for a given sea-level rise scenario, a model has been developed which includes a database at a national scale of present coastal elevation, subsidence, storm surge characteristics, flood protection standard and coastal population density. (The standard of flood protection is estimated using GNP per capita as an 'ability to pay' parameter as no suitable global databases are available). Unlike earlier work, the decline in protection as sea level rises is evaluated. It is further assumed that all coastal populations are presently protected to at least a 1-in-10 year standard. Hence, the area subject to flooding for different global rises of sea level can be calculated. Model results have been validated for the present situation and a one-metre rise in sea level against six national assessments (Egypt, Germany, Guyana, Netherlands, Poland and Vietnam). Global sea-level rise was estimated from the thermal expansion calculated by the Hadley Centre climate model and ice melt contributions quoted in IPCC 1995 (IS92a scenario): the total rise by the 2080s is predicted to be 44 cm. It is assumed that the coastal population will grow at the current trend of twice the national rate.

The results are described using the number of people at risk, which is defined as the average number of people flooded per year by storm surge. Presently the number of people at risk is approximately 10 million, rising to about 30 million in the 2080s under the reference scenario of constant (1990s) flood protection and no sea-level rise. Given the sea-level rise scenario, the number of people at risk increases dramatically being about 700% above the reference scenario by the 2080s (diagram, top left). However, even without sea-level rise, present experience suggests that flood protection will be upgraded in flood-prone countries as national wealth rises, and this will reduce the number of people at risk. As a first estimate of these changes, it is assumed that flood protection is upgraded in line with the projected increase in GNP per capita (but with no additional allowance for sea-level rise). The number of people at risk will still increase by about 250% relative to the reference case by the 2080s (see top figure). Many of these people will experience flooding more frequently than once per year, and it seems likely that they will need to respond in some way (e.g. migration, upgraded sea defences, etc.). Collectively, these results show more dramatic impacts than described by the



The number of people at risk by the 2080s by coastal region under the sea-level rise scenario and constant (1990s) protection, showing the regions where coastal wetlands are most threatened by sea-level rise.

1995 IPCC Second Assessment Report. They suggest that the sea-level rise scenario will cause significant flooding impacts in the coastal zone, particularly in deltaic countries, unless specific adaptation measures for sea-level rise are taken.

Most of the people at risk in the 2080s are concentrated in a few regions, particularly the southern Mediterranean, Africa, southern Asia and South East Asia (see the map at bottom opposite). In addition, relatively high numbers of people at risk are found in five nations which comprise low-lying coral atolls in the Indian and Pacific Oceans (more than 30% of national population in the 2080s assuming 1990s protection).

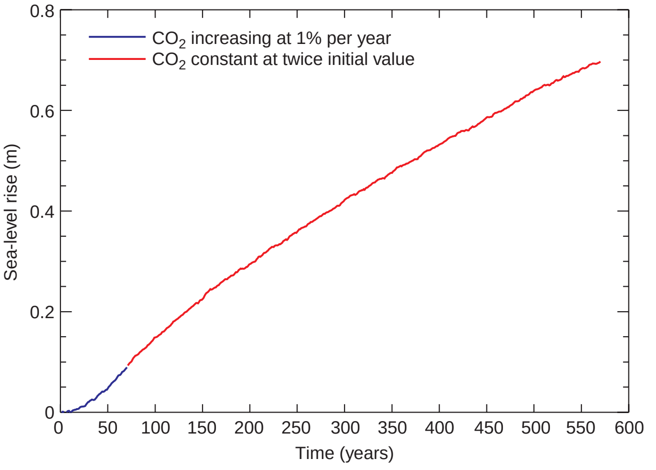
Coastal wetlands

Coastal wetlands, comprising saltmarshes, mangroves and intertidal areas, are sensitive to sea-level rise as their location is intimately linked to sea level. However, they are not passive elements of the landscape and, as sea level rises, so the surface of any coastal wetland rises due to sediment and organic matter input. If this rise keeps pace with sea level the coastal wetland will grow upwards in place, but if it does not, the wetland steadily sinks relative to sea level. Intertidal areas will be steadily submerged. Vegetated wetland systems will be submerged during a tidal cycle for progressively longer periods and may die due to waterlogging, causing a change to bare intertidal areas, or even open water. Therefore, coastal wetlands show a dynamic and non-linear response to sea-level rise. Coastal wetlands with a small tidal range are more vulnerable than those with a large tidal range. Direct losses of coastal wetland due to sea-level rise can be offset by inland wetland migration (upland conversion to wetland as sea level rises). In areas without low-lying coastal upland, or in areas which are protected to stop coastal flooding, wetland migration cannot occur.

The direct wetland response to sea-level rise is modelled by selecting two critical values of sea-level rise, scaled by tidal range; the lower value distinguishes no wetland loss from wetland loss; while the upper value distinguishes partial loss from near-total loss. Loss is modelled linearly between the two threshold values. The potential for wetland migration on to adjacent low-lying upland is evaluated, based on coastal morphology and coastal population density. In addition to the effects of sea-level rise, direct human reclamation is likely to cause large global reductions in coastal wetlands. Based on current trends, 60% of the present wetland stock would be lost by the 2080s without consideration of sea-level rise. It is likely that the loss rate of coastal wetlands will decline with time due to both an increasing rarity, and rising living standards which give the environment a higher ‘value’. Therefore, a reference scenario of losses of 1% a year in the 1990s, declining uniformly to a constant 0.4% a year in the 2020s, was assumed. This gives a loss of 37% of the global wetland stock by the 2080s without sea-level rise.

The middle figure opposite shows the decline in the global stock of wetlands as a function of time. Due to uncertainties concerning model parameters, a low-loss and a high-loss estimate are shown defining a large range of uncertainty. The losses due to sea-level rise are negligible before the 2020s. By the 2080s, the sea-level rise scenario causes the loss of up to 25% of the world’s coastal wetlands. When combined with the direct loss scenario, about 40–50% of the world’s coastal wetlands could be lost by the 2080s. Losses due to sea-level rise vary substantially from region to region. As shown in the map on the opposite page, coastal wetlands are most threatened on the Atlantic coast of North and Central America and around the Mediterranean and the Baltic. This is due to the low tidal range in these areas combined with the limited potential for wetland migration.

Loss of wetlands will impact many sectors including food production (loss of key nursery areas for fisheries), flood and storm protection (storm surges will penetrate further inland), waste treatment and nutrient recycling functions, and as habitat for wildlife. These results stress the need for future effective wetland conservation worldwide.



The rise in sea level due to thermal expansion alone (which accounts for about half of the total rise over the next decades), following an increase in atmospheric concentrations of CO_2 of 1% per year for 70 years (blue), and climate stabilization for a further 500 years (red).

The commitment to sea-level rise

An important aspect of rising sea level is its long timescale. Sea level will rise as meltwater from land ice runs into the ocean and as the ocean waters expand. Even if climate change could be halted, the surface warming already incurred will progressively penetrate deeper and deeper into the ocean, causing sea level to rise still further. The figure above shows how the thermal expansion component of sea-level rise in the Hadley Centre climate model will increase fivefold over the 500 years after all climate change is stopped, and will continue to increase for centuries further. Therefore, sea level will continue to rise after the 2080s, even if further climate change is halted. While impacts have not been evaluated in detail, it seems likely that unavoidably greater losses of wetlands will occur beyond the 2080s.

Conclusions

- Without specific adaptation, sea-level rise will significantly increase the flood risk to coastal populations.
- In absolute numbers, the southern Mediterranean, Africa, southern Asia and South East Asia are most vulnerable to the impacts of flooding.
- Coastal wetlands are expected to decline due to sea-level rise, with the largest losses around the Mediterranean and Baltic and on the Atlantic coast of Central and North America.
- There is a commitment to sea-level rise which means that some impacts will continue to occur for centuries even if climate change is halted.

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For further information, contact Dr Robert Nicholls,
e-mail: robert14@mdx.ac.uk

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