

Climate Change 2001: The Scientific Basis

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Contribution of Working Group I to the Third Assessment Report
of the Intergovernmental Panel on Climate Change

Published for the Intergovernmental Panel on Climate Change

 **CAMBRIDGE**
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS

The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, Melbourne 3166, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

<http://www.cambridge.org>

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First published 2001

Printed in USA at the University Press, New York

A catalogue record for this book is available from the British Library

Library of Congress cataloguing in publication data available

ISBN 0521 80767 0 hardback

ISBN 0521 01495 6 paperback

When citing chapters or the Technical Summary from this report, please use the authors in the order given on the chapter frontpage, for example, Chapter 2 is referenced as:

Folland, C.K., T.R. Karl, J.R. Christy, R.A. Clarke, G.V. Gruza, J. Jouzel, M.E. Mann, J. Oerlemans, M.J. Salinger and S.-W. Wang, 2001: Observed Climate Variability and Change. In: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Reference to the whole report is:

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

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Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change

Based on a draft prepared by:

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Summary for Policymakers

The Third Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC) builds upon past assessments and incorporates new results from the past five years of research on climate change¹. Many hundreds of scientists² from many countries participated in its preparation and review.

This Summary for Policymakers (SPM), which was approved by IPCC member governments in Shanghai in January 2001³, describes the current state of understanding of the climate system and provides estimates of its projected future evolution and their uncertainties. Further details can be found in the underlying report, and the appended Source Information provides cross references to the report's chapters.

An increasing body of observations gives a collective picture of a warming world and other changes in the climate system.

Since the release of the Second Assessment Report (SAR⁴), additional data from new studies of current and palaeoclimates, improved analysis of data sets, more rigorous evaluation of their quality, and comparisons among data from different sources have led to greater understanding of climate change.

The global average surface temperature has increased over the 20th century by about 0.6°C.

- The global average surface temperature (the average of near surface air temperature over land, and sea surface temperature)

has increased since 1861. Over the 20th century the increase has been $0.6 \pm 0.2^\circ\text{C}$ ^{5,6} (Figure 1a). This value is about 0.15°C larger than that estimated by the SAR for the period up to 1994, owing to the relatively high temperatures of the additional years (1995 to 2000) and improved methods of processing the data. These numbers take into account various adjustments, including urban heat island effects. The record shows a great deal of variability; for example, most of the warming occurred during the 20th century, during two periods, 1910 to 1945 and 1976 to 2000.

- Globally, it is very likely⁷ that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record, since 1861 (see Figure 1a).
- New analyses of proxy data for the Northern Hemisphere indicate that the increase in temperature in the 20th century is likely⁷ to have been the largest of any century during the past 1,000 years. It is also likely⁷ that, in the Northern Hemisphere, the 1990s was the warmest decade and 1998 the warmest year (Figure 1b). Because less data are available, less is known about annual averages prior to 1,000 years before present and for conditions prevailing in most of the Southern Hemisphere prior to 1861.
- On average, between 1950 and 1993, night-time daily minimum air temperatures over land increased by about 0.2°C per decade. This is about twice the rate of increase in daytime daily maximum air temperatures (0.1°C per decade). This has lengthened the freeze-free season in many mid- and high latitude regions. The increase in sea surface temperature over this period is about half that of the mean land surface air temperature.

¹ *Climate change* in IPCC usage refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the Framework Convention on Climate Change, where *climate change* refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.

² In total 122 Co-ordinating Lead Authors and Lead Authors, 515 Contributing Authors, 21 Review Editors and 420 Expert Reviewers.

³ Delegations of 99 IPCC member countries participated in the Eighth Session of Working Group I in Shanghai on 17 to 20 January 2001.

⁴ The IPCC Second Assessment Report is referred to in this Summary for Policymakers as the SAR.

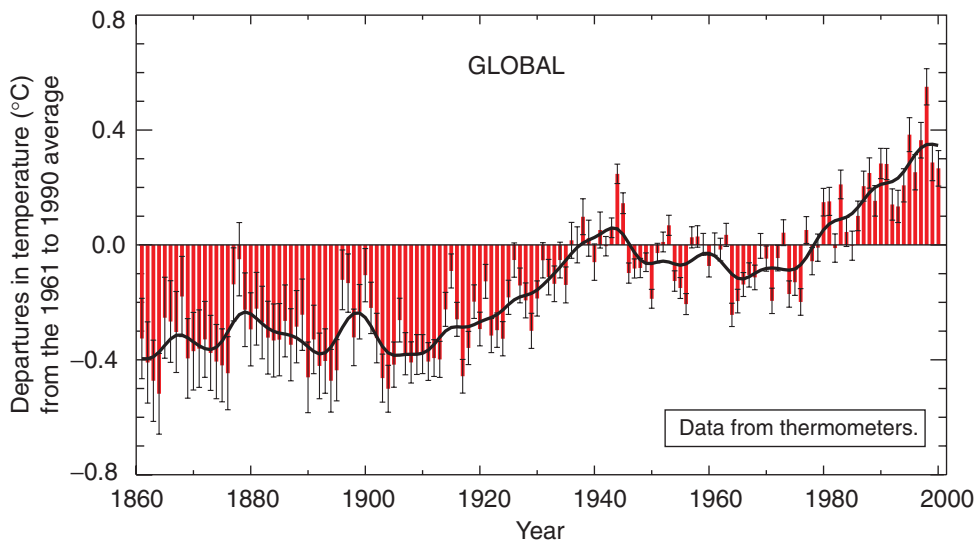
⁵ Generally temperature trends are rounded to the nearest 0.05°C per unit time, the periods often being limited by data availability.

⁶ In general, a 5% statistical significance level is used, and a 95% confidence level.

⁷ In this Summary for Policymakers and in the Technical Summary, the following words have been used where appropriate to indicate judgmental estimates of confidence: *virtually certain* (greater than 99% chance that a result is true); *very likely* (90–99% chance); *likely* (66–90% chance); *medium likelihood* (33–66% chance); *unlikely* (10–33% chance); *very unlikely* (1–10% chance); *exceptionally unlikely* (less than 1% chance). The reader is referred to individual chapters for more details.

Variations of the Earth's surface temperature for:

(a) the past 140 years



(b) the past 1,000 years

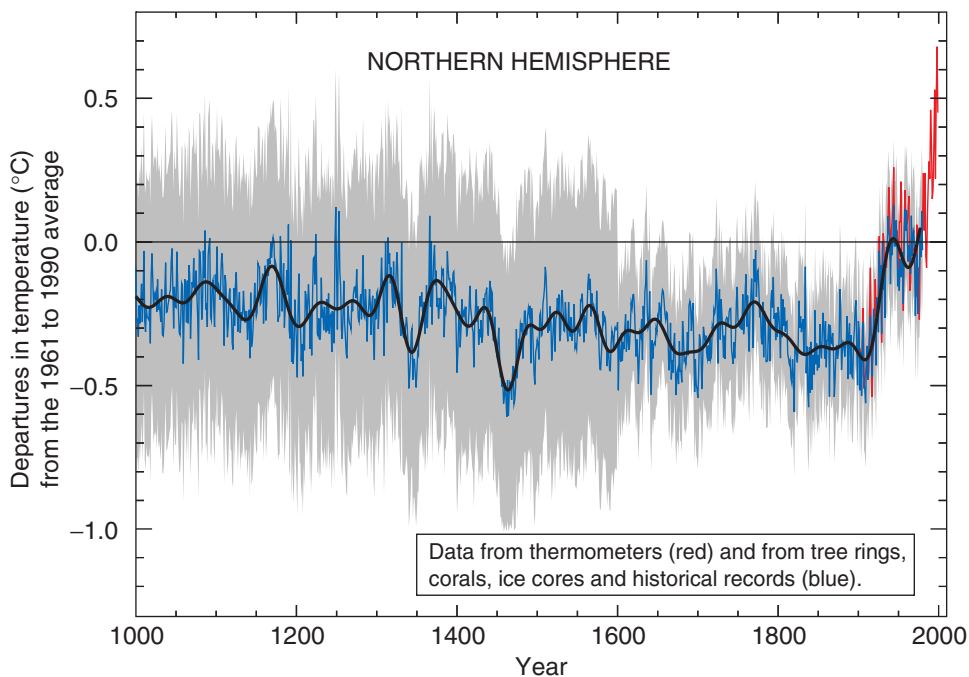


Figure 1: Variations of the Earth's surface temperature over the last 140 years and the last millennium.

(a) The Earth's surface temperature is shown year by year (red bars) and approximately decade by decade (black line, a filtered annual curve suppressing fluctuations below near decadal time-scales). There are uncertainties in the annual data (thin black whisker bars represent the 95% confidence range) due to data gaps, random instrumental errors and uncertainties, uncertainties in bias corrections in the ocean surface temperature data and also in adjustments for urbanisation over the land. Over both the last 140 years and 100 years, the best estimate is that the global average surface temperature has increased by $0.6 \pm 0.2^\circ\text{C}$.

(b) Additionally, the year by year (blue curve) and 50 year average (black curve) variations of the average surface temperature of the Northern Hemisphere for the past 1000 years have been reconstructed from "proxy" data calibrated against thermometer data (see list of the main proxy data in the diagram). The 95% confidence range in the annual data is represented by the grey region. These uncertainties increase in more distant times and are always much larger than in the instrumental record due to the use of relatively sparse proxy data. Nevertheless the rate and duration of warming of the 20th century has been much greater than in any of the previous nine centuries. Similarly, it is likely⁷ that the 1990s have been the warmest decade and 1998 the warmest year of the millennium.

[Based upon (a) Chapter 2, Figure 2.7c and (b) Chapter 2, Figure 2.20]

Temperatures have risen during the past four decades in the lowest 8 kilometres of the atmosphere.

- Since the late 1950s (the period of adequate observations from weather balloons), the overall global temperature increases in the lowest 8 kilometres of the atmosphere and in surface temperature have been similar at 0.1°C per decade.
- Since the start of the satellite record in 1979, both satellite and weather balloon measurements show that the global average temperature of the lowest 8 kilometres of the atmosphere has changed by $+0.05 \pm 0.10^\circ\text{C}$ per decade, but the global average surface temperature has increased significantly by $+0.15 \pm 0.05^\circ\text{C}$ per decade. The difference in the warming rates is statistically significant. This difference occurs primarily over the tropical and sub-tropical regions.
- The lowest 8 kilometres of the atmosphere and the surface are influenced differently by factors such as stratospheric ozone depletion, atmospheric aerosols, and the El Niño phenomenon. Hence, it is physically plausible to expect that over a short time period (e.g., 20 years) there may be differences in temperature trends. In addition, spatial sampling techniques can also explain some of the differences in trends, but these differences are not fully resolved.

Snow cover and ice extent have decreased.

- Satellite data show that there are very likely⁷ to have been decreases of about 10% in the extent of snow cover since the late 1960s, and ground-based observations show that there is very likely⁷ to have been a reduction of about two weeks in the annual duration of lake and river ice cover in the mid- and high latitudes of the Northern Hemisphere, over the 20th century.
- There has been a widespread retreat of mountain glaciers in non-polar regions during the 20th century.
- Northern Hemisphere spring and summer sea-ice extent has decreased by about 10 to 15% since the 1950s. It is likely⁷ that there has been about a 40% decline in Arctic sea-ice thickness during late summer to early autumn in recent decades and a considerably slower decline in winter sea-ice thickness.

Global average sea level has risen and ocean heat content has increased.

- Tide gauge data show that global average sea level rose between 0.1 and 0.2 metres during the 20th century.
- Global ocean heat content has increased since the late 1950s, the period for which adequate observations of sub-surface ocean temperatures have been available.

Changes have also occurred in other important aspects of climate.

- It is very likely⁷ that precipitation has increased by 0.5 to 1% per decade in the 20th century over most mid- and high latitudes of the Northern Hemisphere continents, and it is likely⁷ that rainfall has increased by 0.2 to 0.3% per decade over the tropical (10°N to 10°S) land areas. Increases in the tropics are not evident over the past few decades. It is also likely⁷ that rainfall has decreased over much of the Northern Hemisphere sub-tropical (10°N to 30°N) land areas during the 20th century by about 0.3% per decade. In contrast to the Northern Hemisphere, no comparable systematic changes have been detected in broad latitudinal averages over the Southern Hemisphere. There are insufficient data to establish trends in precipitation over the oceans.
- In the mid- and high latitudes of the Northern Hemisphere over the latter half of the 20th century, it is likely⁷ that there has been a 2 to 4% increase in the frequency of heavy precipitation events. Increases in heavy precipitation events can arise from a number of causes, e.g., changes in atmospheric moisture, thunderstorm activity and large-scale storm activity.
- It is likely⁷ that there has been a 2% increase in cloud cover over mid- to high latitude land areas during the 20th century. In most areas the trends relate well to the observed decrease in daily temperature range.
- Since 1950 it is very likely⁷ that there has been a reduction in the frequency of extreme low temperatures, with a smaller increase in the frequency of extreme high temperatures.

- Warm episodes of the El Niño-Southern Oscillation (ENSO) phenomenon (which consistently affects regional variations of precipitation and temperature over much of the tropics, sub-tropics and some mid-latitude areas) have been more frequent, persistent and intense since the mid-1970s, compared with the previous 100 years.
- Over the 20th century (1900 to 1995), there were relatively small increases in global land areas experiencing severe drought or severe wetness. In many regions, these changes are dominated by inter-decadal and multi-decadal climate variability, such as the shift in ENSO towards more warm events.
- In some regions, such as parts of Asia and Africa, the frequency and intensity of droughts have been observed to increase in recent decades.

Some important aspects of climate appear not to have changed.

- A few areas of the globe have not warmed in recent decades, mainly over some parts of the Southern Hemisphere oceans and parts of Antarctica.
- No significant trends of Antarctic sea-ice extent are apparent since 1978, the period of reliable satellite measurements.
- Changes globally in tropical and extra-tropical storm intensity and frequency are dominated by inter-decadal to multi-decadal variations, with no significant trends evident over the 20th century. Conflicting analyses make it difficult to draw definitive conclusions about changes in storm activity, especially in the extra-tropics.
- No systematic changes in the frequency of tornadoes, thunder days, or hail events are evident in the limited areas analysed.

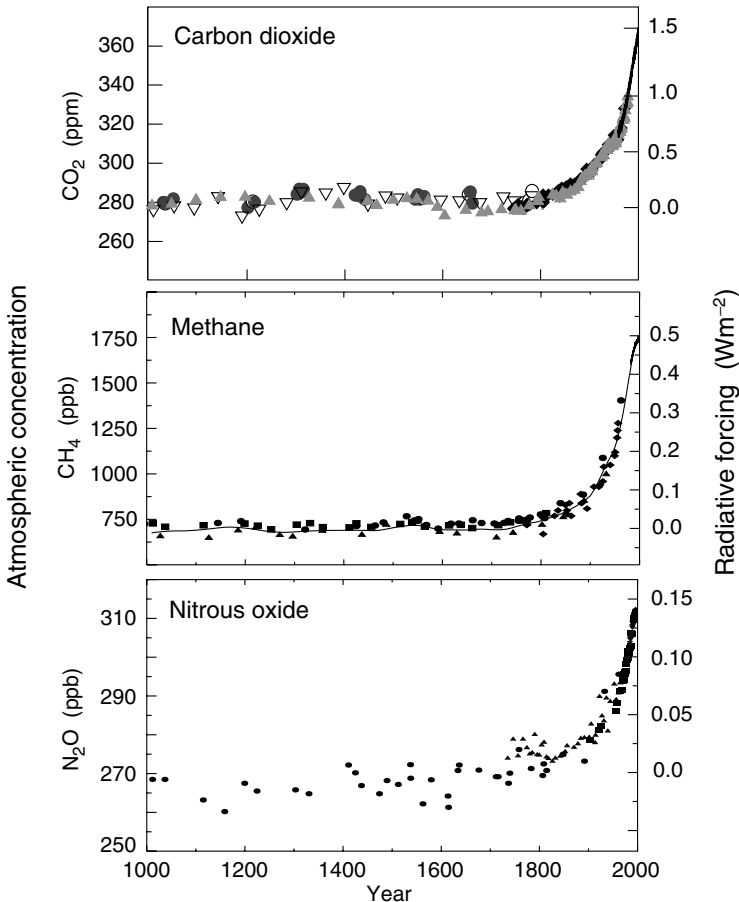
Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate.

Changes in climate occur as a result of both internal variability within the climate system and external factors (both natural and anthropogenic). The influence of external factors on climate can be broadly compared using the concept of radiative forcing⁸. A positive radiative forcing, such as that produced by increasing concentrations of greenhouse gases, tends to warm the surface. A negative radiative forcing, which can arise from an increase in some types of aerosols (microscopic airborne particles) tends to cool the surface. Natural factors, such as changes in solar output or explosive volcanic activity, can also cause radiative forcing. Characterisation of these climate forcing agents and their changes over time (see Figure 2) is required to understand past climate changes in the context of natural variations and to project what climate changes could lie ahead. Figure 3 shows current estimates of the radiative forcing due to increased concentrations of atmospheric constituents and other mechanisms.

⁸ *Radiative forcing* is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in Watts per square metre (Wm^{-2}).

Indicators of the human influence on the atmosphere during the Industrial Era

(a) Global atmospheric concentrations of three well mixed greenhouse gases



(b) Sulphate aerosols deposited in Greenland ice

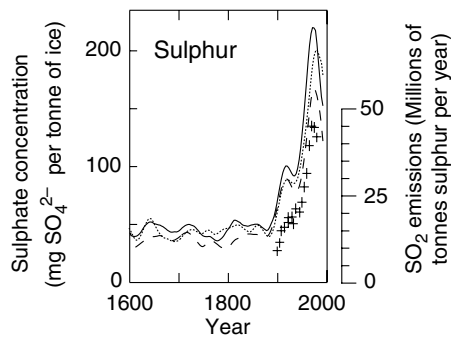


Figure 2: Long records of past changes in atmospheric composition provide the context for the influence of anthropogenic emissions.

(a) shows changes in the atmospheric concentrations of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) over the past 1000 years. The ice core and firn data for several sites in Antarctica and Greenland (shown by different symbols) are supplemented with the data from direct atmospheric samples over the past few decades (shown by the line for CO₂ and incorporated in the curve representing the global average of CH₄). The estimated positive radiative forcing of the climate system from these gases is indicated on the right-hand scale. Since these gases have atmospheric lifetimes of a decade or more, they are well mixed, and their concentrations reflect emissions from sources throughout the globe. All three records show effects of the large and increasing growth in anthropogenic emissions during the Industrial Era.

(b) illustrates the influence of industrial emissions on atmospheric sulphate concentrations, which produce negative radiative forcing. Shown is the time history of the concentrations of sulphate, not in the atmosphere but in ice cores in Greenland (shown by lines; from which the episodic effects of volcanic eruptions have been removed). Such data indicate the local deposition of sulphate aerosols at the site, reflecting sulphur dioxide (SO₂) emissions at mid-latitudes in the Northern Hemisphere. This record, albeit more regional than that of the globally-mixed greenhouse gases, demonstrates the large growth in anthropogenic SO₂ emissions during the Industrial Era. The pluses denote the relevant regional estimated SO₂ emissions (right-hand scale).

[Based upon (a) Chapter 3, Figure 3.2b (CO₂); Chapter 4, Figure 4.1a and b (CH₄) and Chapter 4, Figure 4.2 (N₂O) and (b) Chapter 5, Figure 5.4a]

Concentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities.

- The atmospheric concentration of carbon dioxide (CO₂) has increased by 31% since 1750. The present CO₂ concentration has not been exceeded during the past 420,000 years and likely⁷ not during the past 20 million years. The current rate of increase is unprecedented during at least the past 20,000 years.
- About three-quarters of the anthropogenic emissions of CO₂ to the atmosphere during the past 20 years is due to fossil fuel burning. The rest is predominantly due to land-use change, especially deforestation.
- Currently the ocean and the land together are taking up about half of the anthropogenic CO₂ emissions. On land, the uptake of anthropogenic CO₂ very likely⁷ exceeded the release of CO₂ by deforestation during the 1990s.
- The rate of increase of atmospheric CO₂ concentration has been about 1.5 ppm⁹ (0.4%) per year over the past two decades. During the 1990s the year to year increase varied from 0.9 ppm (0.2%) to 2.8 ppm (0.8%). A large part of this variability is due to the effect of climate variability (e.g., El Niño events) on CO₂ uptake and release by land and oceans.
- The atmospheric concentration of methane (CH₄) has increased by 1060 ppb⁹ (151%) since 1750 and continues to increase. The present CH₄ concentration has not been exceeded during the past 420,000 years. The annual growth in CH₄ concentration slowed and became more variable in the 1990s, compared with the 1980s. Slightly more than half of current CH₄ emissions are anthropogenic (e.g., use of fossil fuels, cattle, rice agriculture and landfills). In addition, carbon monoxide (CO) emissions have recently been identified as a cause of increasing CH₄ concentration.
- The atmospheric concentration of nitrous oxide (N₂O) has increased by 46 ppb (17%) since 1750 and continues to increase. The present N₂O concentration has not been exceeded during at least the past thousand years. About a third of current N₂O emissions are anthropogenic (e.g., agricultural soils, cattle feed lots and chemical industry).
- Since 1995, the atmospheric concentrations of many of those halocarbon gases that are both ozone-depleting and greenhouse gases (e.g., CFC₁₃ and CF₂Cl₂), are either increasing more slowly or decreasing, both in response to reduced emissions under the regulations of the Montreal Protocol and its Amendments. Their substitute compounds (e.g., CHF₂Cl and CF₃CH₂F) and some other synthetic compounds (e.g., perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆)) are also greenhouse gases, and their concentrations are currently increasing.
- The radiative forcing due to increases of the well-mixed greenhouse gases from 1750 to 2000 is estimated to be 2.43 Wm⁻²: 1.46 Wm⁻² from CO₂; 0.48 Wm⁻² from CH₄; 0.34 Wm⁻² from the halocarbons; and 0.15 Wm⁻² from N₂O. (See Figure 3, where the uncertainties are also illustrated.)
- The observed depletion of the stratospheric ozone (O₃) layer from 1979 to 2000 is estimated to have caused a negative radiative forcing (-0.15 Wm⁻²). Assuming full compliance with current halocarbon regulations, the positive forcing of the halocarbons will be reduced as will the magnitude of the negative forcing from stratospheric ozone depletion as the ozone layer recovers over the 21st century.
- The total amount of O₃ in the troposphere is estimated to have increased by 36% since 1750, due primarily to anthropogenic emissions of several O₃-forming gases. This corresponds to a positive radiative forcing of 0.35 Wm⁻². O₃ forcing varies considerably by region and responds much more quickly to changes in emissions than the long-lived greenhouse gases, such as CO₂.

⁹ ppm (parts per million) or ppb (parts per billion, 1 billion = 1,000 million) is the ratio of the number of greenhouse gas molecules to the total number of molecules of dry air. For example: 300 ppm means 300 molecules of a greenhouse gas per million molecules of dry air.

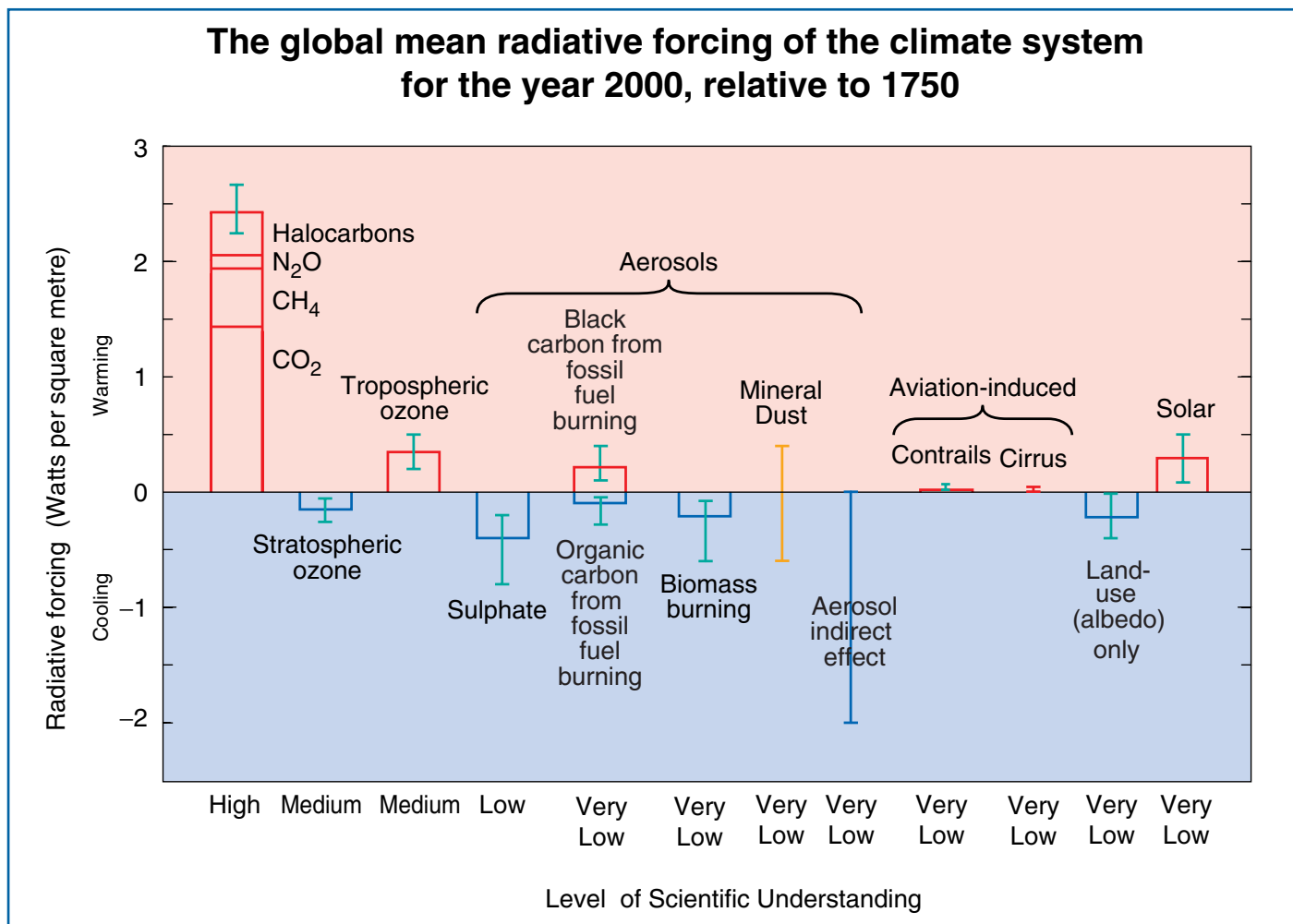


Figure 3: Many external factors force climate change.

These radiative forcings arise from changes in the atmospheric composition, alteration of surface reflectance by land use, and variation in the output of the sun. Except for solar variation, some form of human activity is linked to each. The rectangular bars represent estimates of the contributions of these forcings – some of which yield warming, and some cooling. Forcing due to episodic volcanic events, which lead to a negative forcing lasting only for a few years, is not shown. The indirect effect of aerosols shown is their effect on the size and number of cloud droplets. A second indirect effect of aerosols on clouds, namely their effect on cloud lifetime, which would also lead to a negative forcing, is not shown. Effects of aviation on greenhouse gases are included in the individual bars. The vertical line about the rectangular bars indicates a range of estimates, guided by the spread in the published values of the forcings and physical understanding. Some of the forcings possess a much greater degree of certainty than others. A vertical line without a rectangular bar denotes a forcing for which no best estimate can be given owing to large uncertainties. The overall level of scientific understanding for each forcing varies considerably, as noted. Some of the radiative forcing agents are well mixed over the globe, such as CO₂, thereby perturbing the global heat balance. Others represent perturbations with stronger regional signatures because of their spatial distribution, such as aerosols. For this and other reasons, a simple sum of the positive and negative bars cannot be expected to yield the net effect on the climate system. The simulations of this assessment report (for example, Figure 5) indicate that the estimated net effect of these perturbations is to have warmed the global climate since 1750. [Based upon Chapter 6, Figure 6.6]

Anthropogenic aerosols are short-lived and mostly produce negative radiative forcing.

- The major sources of anthropogenic aerosols are fossil fuel and biomass burning. These sources are also linked to degradation of air quality and acid deposition.
- Since the SAR, significant progress has been achieved in better characterising the direct radiative roles of different types of aerosols. Direct radiative forcing is estimated to be -0.4 Wm^{-2} for sulphate, -0.2 Wm^{-2} for biomass burning aerosols, -0.1 Wm^{-2} for fossil fuel organic carbon and $+0.2 \text{ Wm}^{-2}$ for fossil fuel black carbon aerosols. There is much less confidence in the ability to quantify the total aerosol direct effect, and its evolution over time, than that for the gases listed above. Aerosols also vary considerably by region and respond quickly to changes in emissions.
- In addition to their direct radiative forcing, aerosols have an indirect radiative forcing through their effects on clouds. There is now more evidence for this indirect effect, which is negative, although of very uncertain magnitude.

Natural factors have made small contributions to radiative forcing over the past century.

- The radiative forcing due to changes in solar irradiance for the period since 1750 is estimated to be about $+0.3 \text{ Wm}^{-2}$, most of which occurred during the first half of the 20th century. Since the late 1970s, satellite instruments have observed small oscillations due to the 11-year solar cycle. Mechanisms for the amplification of solar effects on climate have been proposed, but currently lack a rigorous theoretical or observational basis.
- Stratospheric aerosols from explosive volcanic eruptions lead to negative forcing, which lasts a few years. Several major eruptions occurred in the periods 1880 to 1920 and 1960 to 1991.
- The combined change in radiative forcing of the two major natural factors (solar variation and volcanic aerosols) is estimated to be negative for the past two, and possibly the past four, decades.

Confidence in the ability of models to project future climate has increased.

Complex physically-based climate models are required to provide detailed estimates of feedbacks and of regional features. Such models cannot yet simulate all aspects of climate (e.g., they still cannot account fully for the observed trend in the surface-troposphere temperature difference since 1979) and there are particular uncertainties associated with clouds and their interaction with radiation and aerosols. Nevertheless, confidence in the ability of these models to provide useful projections of future climate has improved due to their demonstrated performance on a range of space and time-scales.

- Understanding of climate processes and their incorporation in climate models have improved, including water vapour, sea-ice dynamics, and ocean heat transport.
- Some recent models produce satisfactory simulations of current climate without the need for non-physical adjustments of heat and water fluxes at the ocean-atmosphere interface used in earlier models.
- Simulations that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century (Figure 4). However, contributions from some additional processes and forcings may not have been included in the models. Nevertheless, the large-scale consistency between models and observations can be used to provide an independent check on projected warming rates over the next few decades under a given emissions scenario.
- Some aspects of model simulations of ENSO, monsoons and the North Atlantic Oscillation, as well as selected periods of past climate, have improved.

There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.

The SAR concluded: “The balance of evidence suggests a discernible human influence on global climate”. That report also noted that the anthropogenic signal was still emerging from the background of natural climate variability. Since the SAR, progress has been made in reducing uncertainty, particularly with respect to distinguishing and quantifying the magnitude of responses to different external influences. Although many of the sources of uncertainty identified in the SAR still remain to some degree, new evidence and improved understanding support an updated conclusion.

- There is a longer and more closely scrutinised temperature record and new model estimates of variability. The warming over the past 100 years is very unlikely⁷ to be due to internal variability alone, as estimated by current models. Reconstructions of climate data for the past 1,000 years (Figure 1b) also indicate that this warming was unusual and is unlikely⁷ to be entirely natural in origin.
- There are new estimates of the climate response to natural and anthropogenic forcing, and new detection techniques have been applied. Detection and attribution studies consistently find evidence for an anthropogenic signal in the climate record of the last 35 to 50 years.
- Simulations of the response to natural forcings alone (i.e., the response to variability in solar irradiance and volcanic eruptions) do not explain the warming in the second half of the 20th century (see for example Figure 4a). However, they indicate that natural forcings may have contributed to the observed warming in the first half of the 20th century.
- The warming over the last 50 years due to anthropogenic greenhouse gases can be identified despite uncertainties in forcing due to anthropogenic sulphate aerosol and natural factors (volcanoes and solar irradiance). The anthropogenic sulphate aerosol forcing, while uncertain, is negative over this period and therefore cannot explain the warming. Changes in natural forcing during most of this period are also estimated to be negative and are unlikely⁷ to explain the warming.

- Detection and attribution studies comparing model simulated changes with the observed record can now take into account uncertainty in the magnitude of modelled response to external forcing, in particular that due to uncertainty in climate sensitivity.
- Most of these studies find that, over the last 50 years, the estimated rate and magnitude of warming due to increasing concentrations of greenhouse gases alone are comparable with, or larger than, the observed warming. Furthermore, most model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this period.
- The best agreement between model simulations and observations over the last 140 years has been found when all the above anthropogenic and natural forcing factors are combined, as shown in Figure 4c. These results show that the forcings included are sufficient to explain the observed changes, but do not exclude the possibility that other forcings may also have contributed.

In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely⁷ to have been due to the increase in greenhouse gas concentrations.

Furthermore, it is very likely⁷ that the 20th century warming has contributed significantly to the observed sea level rise, through thermal expansion of sea water and widespread loss of land ice. Within present uncertainties, observations and models are both consistent with a lack of significant acceleration of sea level rise during the 20th century.

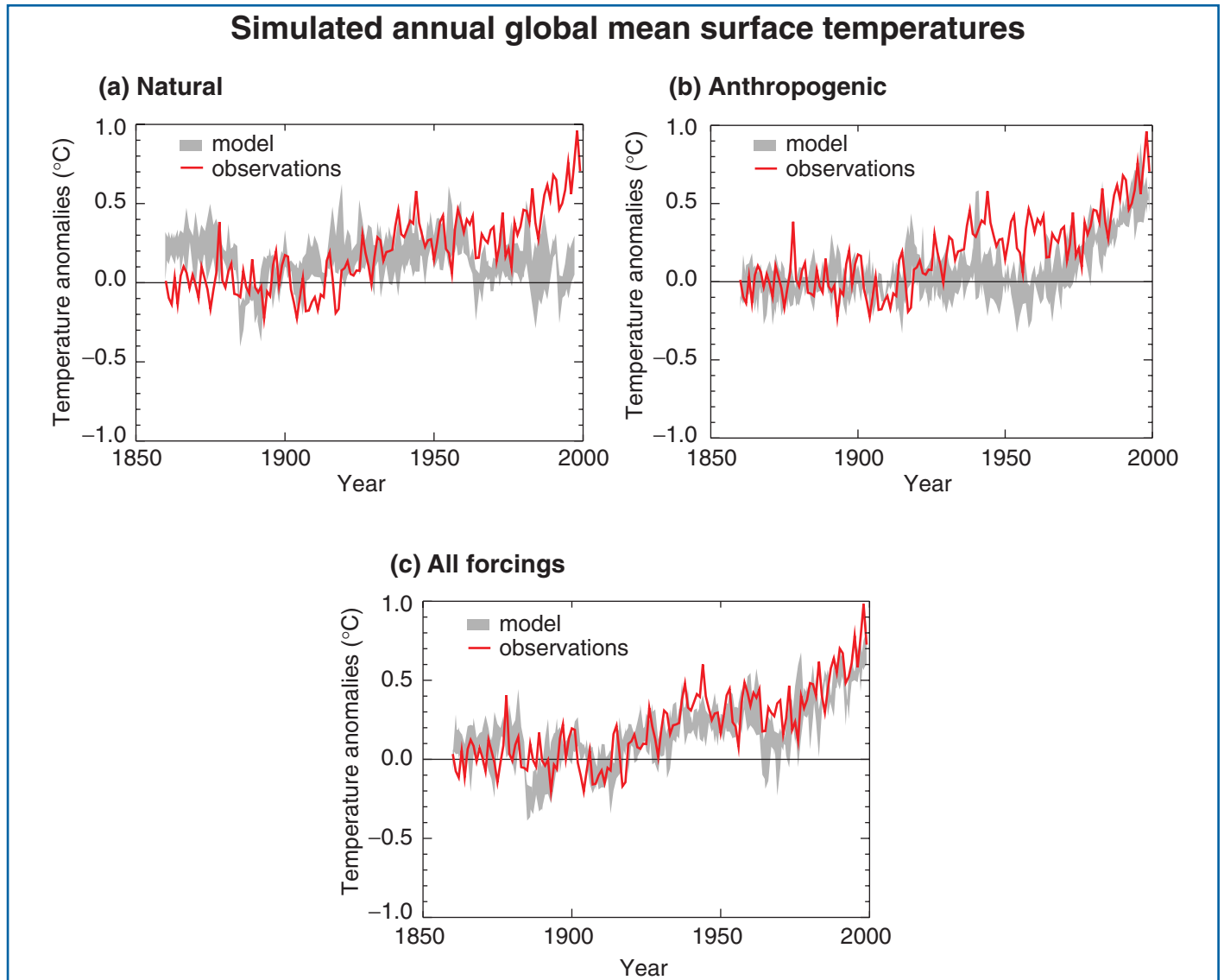


Figure 4: Simulating the Earth's temperature variations, and comparing the results to measured changes, can provide insight into the underlying causes of the major changes.

A climate model can be used to simulate the temperature changes that occur both from natural and anthropogenic causes. The simulations represented by the band in (a) were done with only natural forcings: solar variation and volcanic activity. Those encompassed by the band in (b) were done with anthropogenic forcings: greenhouse gases and an estimate of sulphate aerosols, and those encompassed by the band in (c) were done with both natural and anthropogenic forcings included. From (b), it can be seen that inclusion of anthropogenic forcings provides a plausible explanation for a substantial part of the observed temperature changes over the past century, but the best match with observations is obtained in (c) when both natural and anthropogenic factors are included. These results show that the forcings included are sufficient to explain the observed changes, but do not exclude the possibility that other forcings may also have contributed. The bands of model results presented here are for four runs from the same model. Similar results to those in (b) are obtained with other models with anthropogenic forcing. [Based upon Chapter 12, Figure 12.7]

Human influences will continue to change atmospheric composition throughout the 21st century.

Models have been used to make projections of atmospheric concentrations of greenhouse gases and aerosols, and hence of future climate, based upon emissions scenarios from the IPCC Special Report on Emission Scenarios (SRES) (Figure 5). These scenarios were developed to update the IS92 series, which were used in the SAR and are shown for comparison here in some cases.

Greenhouse gases

- Emissions of CO₂ due to fossil fuel burning are virtually certain⁷ to be the dominant influence on the trends in atmospheric CO₂ concentration during the 21st century.
- As the CO₂ concentration of the atmosphere increases, ocean and land will take up a decreasing fraction of anthropogenic CO₂ emissions. The net effect of land and ocean climate feedbacks as indicated by models is to further increase projected atmospheric CO₂ concentrations, by reducing both the ocean and land uptake of CO₂.
- By 2100, carbon cycle models project atmospheric CO₂ concentrations of 540 to 970 ppm for the illustrative SRES scenarios (90 to 250% above the concentration of 280 ppm in the year 1750), Figure 5b. These projections include the land and ocean climate feedbacks. Uncertainties, especially about the magnitude of the climate feedback from the terrestrial biosphere, cause a variation of about –10 to +30% around each scenario. The total range is 490 to 1260 ppm (75 to 350% above the 1750 concentration).
- Changing land use could influence atmospheric CO₂ concentration. Hypothetically, if all of the carbon released by historical land-use changes could be restored to the terrestrial biosphere over the course of the century (e.g., by reforestation), CO₂ concentration would be reduced by 40 to 70 ppm.
- Model calculations of the concentrations of the non-CO₂ greenhouse gases by 2100 vary considerably across the SRES illustrative scenarios, with CH₄ changing by –190 to +1,970 ppb (present concentration 1,760 ppb), N₂O changing

by +38 to +144 ppb (present concentration 316 ppb), total tropospheric O₃ changing by –12 to +62%, and a wide range of changes in concentrations of HFCs, PFCs and SF₆, all relative to the year 2000. In some scenarios, total tropospheric O₃ would become as important a radiative forcing agent as CH₄ and, over much of the Northern Hemisphere, would threaten the attainment of current air quality targets.

- Reductions in greenhouse gas emissions and the gases that control their concentration would be necessary to stabilise radiative forcing. For example, for the most important anthropogenic greenhouse gas, carbon cycle models indicate that stabilisation of atmospheric CO₂ concentrations at 450, 650 or 1,000 ppm would require global anthropogenic CO₂ emissions to drop below 1990 levels, within a few decades, about a century, or about two centuries, respectively, and continue to decrease steadily thereafter. Eventually CO₂ emissions would need to decline to a very small fraction of current emissions.

Aerosols

- The SRES scenarios include the possibility of either increases or decreases in anthropogenic aerosols (e.g., sulphate aerosols (Figure 5c), biomass aerosols, black and organic carbon aerosols) depending on the extent of fossil fuel use and policies to abate polluting emissions. In addition, natural aerosols (e.g., sea salt, dust and emissions leading to the production of sulphate and carbon aerosols) are projected to increase as a result of changes in climate.

Radiative forcing over the 21st century

- For the SRES illustrative scenarios, relative to the year 2000, the global mean radiative forcing due to greenhouse gases continues to increase through the 21st century, with the fraction due to CO₂ projected to increase from slightly more than half to about three quarters. The change in the direct plus indirect aerosol radiative forcing is projected to be smaller in magnitude than that of CO₂.

Global average temperature and sea level are projected to rise under all IPCC SRES scenarios.

In order to make projections of future climate, models incorporate past, as well as future emissions of greenhouse gases and aerosols. Hence, they include estimates of warming to date and the commitment to future warming from past emissions.

Temperature

- The globally averaged surface temperature is projected to increase by 1.4 to 5.8°C (Figure 5d) over the period 1990 to 2100. These results are for the full range of 35 SRES scenarios, based on a number of climate models^{10,11}.
- Temperature increases are projected to be greater than those in the SAR, which were about 1.0 to 3.5°C based on the six IS92 scenarios. The higher projected temperatures and the wider range are due primarily to the lower projected sulphur dioxide emissions in the SRES scenarios relative to the IS92 scenarios.
- The projected rate of warming is much larger than the observed changes during the 20th century and is very likely⁷ to be without precedent during at least the last 10,000 years, based on palaeoclimate data.
- By 2100, the range in the surface temperature response across the group of climate models run with a given scenario is comparable to the range obtained from a single model run with the different SRES scenarios.
- On timescales of a few decades, the current observed rate of warming can be used to constrain the projected response to a given emissions scenario despite uncertainty in climate sensitivity. This approach suggests that anthropogenic

warming is likely⁷ to lie in the range of 0.1 to 0.2°C per decade over the next few decades under the IS92a scenario, similar to the corresponding range of projections of the simple model used in Figure 5d.

- Based on recent global model simulations, it is very likely⁷ that nearly all land areas will warm more rapidly than the global average, particularly those at northern high latitudes in the cold season. Most notable of these is the warming in the northern regions of North America, and northern and central Asia, which exceeds global mean warming in each model by more than 40%. In contrast, the warming is less than the global mean change in south and southeast Asia in summer and in southern South America in winter.
- Recent trends for surface temperature to become more El Niño-like in the tropical Pacific, with the eastern tropical Pacific warming more than the western tropical Pacific, with a corresponding eastward shift of precipitation, are projected to continue in many models.

Precipitation

- Based on global model simulations and for a wide range of scenarios, global average water vapour concentration and precipitation are projected to increase during the 21st century. By the second half of the 21st century, it is likely⁷ that precipitation will have increased over northern mid- to high latitudes and Antarctica in winter. At low latitudes there are both regional increases and decreases over land areas. Larger year to year variations in precipitation are very likely⁷ over most areas where an increase in mean precipitation is projected.

¹⁰ Complex physically based climate models are the main tool for projecting future climate change. In order to explore the full range of scenarios, these are complemented by simple climate models calibrated to yield an equivalent response in temperature and sea level to complex climate models. These projections are obtained using a simple climate model whose climate sensitivity and ocean heat uptake are calibrated to each of seven complex climate models. The climate sensitivity used in the simple model ranges from 1.7 to 4.2°C, which is comparable to the commonly accepted range of 1.5 to 4.5°C.

¹¹ This range does not include uncertainties in the modelling of radiative forcing, e.g. aerosol forcing uncertainties. A small carbon-cycle climate feedback is included.

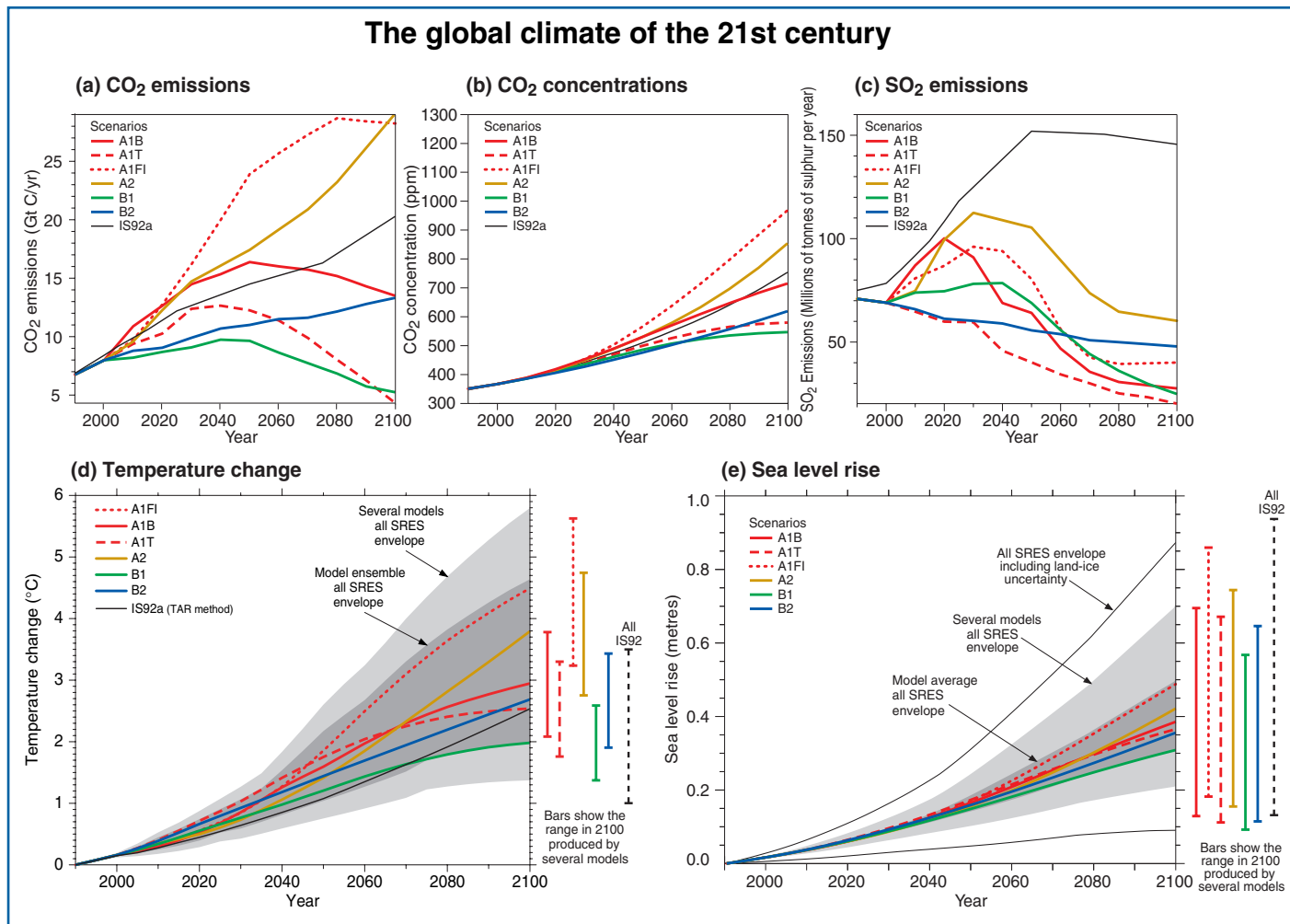


Figure 5: The global climate of the 21st century will depend on natural changes and the response of the climate system to human activities.

Climate models project the response of many climate variables – such as increases in global surface temperature and sea level – to various scenarios of greenhouse gas and other human-related emissions. (a) shows the CO₂ emissions of the six illustrative SRES scenarios, which are summarised in the box on page 18, along with IS92a for comparison purposes with the SAR. (b) shows projected CO₂ concentrations. (c) shows anthropogenic SO₂ emissions. Emissions of other gases and other aerosols were included in the model but are not shown in the figure. (d) and (e) show the projected temperature and sea level responses, respectively. The “several models all SRES envelope” in (d) and (e) shows the temperature and sea level rise, respectively, for the simple model when tuned to a number of complex models with a range of climate sensitivities. All SRES envelopes refer to the full range of 35 SRES scenarios. The “model average all SRES envelope” shows the average from these models for the range of scenarios. Note that the warming and sea level rise from these emissions would continue well beyond 2100. Also note that this range does not allow for uncertainty relating to ice dynamical changes in the West Antarctic ice sheet, nor does it account for uncertainties in projecting non-sulphate aerosols and greenhouse gas concentrations. [Based upon (a) Chapter 3, Figure 3.12, (b) Chapter 3, Figure 3.12, (c) Chapter 5, Figure 5.13, (d) Chapter 9, Figure 9.14, (e) Chapter 11, Figure 11.12, Appendix II]

Extreme Events

Table 1 depicts an assessment of confidence in observed changes in extremes of weather and climate during the latter half of the 20th century (left column) and in projected changes during the 21st century (right column)^a. This assessment relies on observational and modelling studies, as well as the physical plausibility of future projections across all commonly-used scenarios and is based on expert judgement⁷.

- For some other extreme phenomena, many of which may have important impacts on the environment and society, there is currently insufficient information to assess recent trends, and climate models currently lack the spatial detail required to make confident projections. For example, very small-scale phenomena, such as thunderstorms, tornadoes, hail and lightning, are not simulated in climate models.

Table 1: Estimates of confidence in observed and projected changes in extreme weather and climate events.

Confidence in observed changes (latter half of the 20th century)	Changes in Phenomenon	Confidence in projected changes (during the 21st century)
Likely ⁷	Higher maximum temperatures and more hot days over nearly all land areas	Very likely ⁷
Very likely ⁷	Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely ⁷
Very likely ⁷	Reduced diurnal temperature range over most land areas	Very likely ⁷
Likely ⁷ , over many areas	Increase of heat index¹² over land areas	Very likely ⁷ , over most areas
Likely ⁷ , over many Northern Hemisphere mid- to high latitude land areas	More intense precipitation events^b	Very likely ⁷ , over many areas
Likely ⁷ , in a few areas	Increased summer continental drying and associated risk of drought	Likely ⁷ , over most mid-latitude continental interiors. (Lack of consistent projections in other areas)
Not observed in the few analyses available	Increase in tropical cyclone peak wind intensities^c	Likely ⁷ , over some areas
Insufficient data for assessment	Increase in tropical cyclone mean and peak precipitation intensities^c	Likely ⁷ , over some areas

^a For more details see Chapter 2 (observations) and Chapter 9, 10 (projections).

^b For other areas, there are either insufficient data or conflicting analyses.

^c Past and future changes in tropical cyclone location and frequency are uncertain.

¹² Heat index: A combination of temperature and humidity that measures effects on human comfort.

El Niño

- Confidence in projections of changes in future frequency, amplitude, and spatial pattern of El Niño events in the tropical Pacific is tempered by some shortcomings in how well El Niño is simulated in complex models. Current projections show little change or a small increase in amplitude for El Niño events over the next 100 years.
- Even with little or no change in El Niño amplitude, global warming is likely⁷ to lead to greater extremes of drying and heavy rainfall and increase the risk of droughts and floods that occur with El Niño events in many different regions.

Monsoons

- It is likely⁷ that warming associated with increasing greenhouse gas concentrations will cause an increase of Asian summer monsoon precipitation variability. Changes in monsoon mean duration and strength depend on the details of the emission scenario. The confidence in such projections is also limited by how well the climate models simulate the detailed seasonal evolution of the monsoons.

Thermohaline circulation

- Most models show weakening of the ocean thermohaline circulation which leads to a reduction of the heat transport into high latitudes of the Northern Hemisphere. However, even in models where the thermohaline circulation weakens, there is still a warming over Europe due to increased greenhouse gases. The current projections using climate models do not exhibit a complete shut-down of the thermohaline circulation by 2100. Beyond 2100, the thermohaline circulation could completely, and possibly irreversibly, shut-down in either hemisphere if the change in radiative forcing is large enough and applied long enough.

Snow and ice

- Northern Hemisphere snow cover and sea-ice extent are projected to decrease further.
- Glaciers and ice caps are projected to continue their widespread retreat during the 21st century.
- The Antarctic ice sheet is likely⁷ to gain mass because of greater precipitation, while the Greenland ice sheet is likely⁷ to lose mass because the increase in runoff will exceed the precipitation increase.
- Concerns have been expressed about the stability of the West Antarctic ice sheet because it is grounded below sea level. However, loss of grounded ice leading to substantial sea level rise from this source is now widely agreed to be very unlikely⁷ during the 21st century, although its dynamics are still inadequately understood, especially for projections on longer time-scales.

Sea level

- Global mean sea level is projected to rise by 0.09 to 0.88 metres between 1990 and 2100, for the full range of SRES scenarios. This is due primarily to thermal expansion and loss of mass from glaciers and ice caps (Figure 5e). The range of sea level rise presented in the SAR was 0.13 to 0.94 metres based on the IS92 scenarios. Despite the higher temperature change projections in this assessment, the sea level projections are slightly lower, primarily due to the use of improved models, which give a smaller contribution from glaciers and ice sheets.

Anthropogenic climate change will persist for many centuries.

- Emissions of long-lived greenhouse gases (i.e., CO₂, N₂O, PFCs, SF₆) have a lasting effect on atmospheric composition, radiative forcing and climate. For example, several centuries after CO₂ emissions occur, about a quarter of the increase in CO₂ concentration caused by these emissions is still present in the atmosphere.
- After greenhouse gas concentrations have stabilised, global average surface temperatures would rise at a rate of only a few tenths of a degree per century rather than several degrees per century as projected for the 21st century without stabilisation. The lower the level at which concentrations are stabilised, the smaller the total temperature change.
- Global mean surface temperature increases and rising sea level from thermal expansion of the ocean are projected to continue for hundreds of years after stabilisation of greenhouse gas concentrations (even at present levels), owing to the long timescales on which the deep ocean adjusts to climate change.
- Ice sheets will continue to react to climate warming and contribute to sea level rise for thousands of years after climate has been stabilised. Climate models indicate that the local warming over Greenland is likely⁷ to be one to three times the global average. Ice sheet models project that a local warming of larger than 3°C, if sustained for millennia, would lead to virtually a complete melting of the Greenland ice sheet with a resulting sea level rise of about 7 metres. A local warming of 5.5°C, if sustained for 1,000 years, would be likely⁷ to result in a contribution from Greenland of about 3 metres to sea level rise.
- Current ice dynamic models suggest that the West Antarctic ice sheet could contribute up to 3 metres to sea level rise over the next 1,000 years, but such results are strongly dependent on model assumptions regarding climate change scenarios, ice dynamics and other factors.

Further action is required to address remaining gaps in information and understanding.

Further research is required to improve the ability to detect, attribute and understand climate change, to reduce uncertainties and to project future climate changes. In particular, there is a need for additional systematic and sustained observations, modelling and process studies. A serious concern is the decline of observational networks. The following are high priority areas for action.

- Systematic observations and reconstructions:
 - Reverse the decline of observational networks in many parts of the world.
 - Sustain and expand the observational foundation for climate studies by providing accurate, long-term, consistent data including implementation of a strategy for integrated global observations.
 - Enhance the development of reconstructions of past climate periods.
 - Improve the observations of the spatial distribution of greenhouse gases and aerosols.
- Modelling and process studies:
 - Improve understanding of the mechanisms and factors leading to changes in radiative forcing.
 - Understand and characterise the important unresolved processes and feedbacks, both physical and biogeochemical, in the climate system.
 - Improve methods to quantify uncertainties of climate projections and scenarios, including long-term ensemble simulations using complex models.
 - Improve the integrated hierarchy of global and regional climate models with a focus on the simulation of climate variability, regional climate changes and extreme events.
 - Link more effectively models of the physical climate and the biogeochemical system, and in turn improve coupling with descriptions of human activities.

Cutting across these foci are crucial needs associated with strengthening international co-operation and co-ordination in order to better utilise scientific, computational and observational resources. This should also promote the free exchange of data among scientists. A special need is to increase the observational and research capacities in many regions, particularly in developing countries. Finally, as is the goal of this assessment, there is a continuing imperative to communicate research advances in terms that are relevant to decision making.

The Emissions Scenarios of the Special Report on Emissions Scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

Source Information: Summary for Policymakers

This appendix provides the cross-reference of the topics in the Summary for Policymakers (page and bullet point topic) to the sections of the chapters of the full report that contain expanded information about the topic.

An increasing body of observations gives a collective picture of a warming world and other changes in the climate system.

SPM Page	Cross-Reference: SPM Topic – Chapter Section
2	<i>The global average surface temperature has increased over the 20th century by about 0.6°C.</i> ● Chapter 2.2.2 ● Chapter 2.2.2 ● Chapter 2.3 ● Chapter 2.2.2
4	<i>Temperatures have risen during the past four decades in the lowest 8 kilometres of the atmosphere.</i> ● Chapter 2.2.3 and 2.2.4 ● Chapter 2.2.3 and 2.2.4 ● Chapter 2.2.3, 2.2.4 and Chapter 12.3.2
4	<i>Snow cover and ice extent have decreased.</i> All three bullet points: Chapter 2.2.5 and 2.2.6
4	<i>Global average sea level has risen and ocean heat content has increased.</i> ● Chapter 11.3.2 ● Chapter 2.2.2 and Chapter 11.2.1
4 – 5	<i>Changes have also occurred in other important aspects of climate.</i> ● Chapter 2.5.2 ● Chapter 2.7.2 ● Chapter 2.2.2 and 2.5.5 ● Chapter 2.7.2 ● Chapter 2.6.2 and 2.6.3 ● Chapter 2.7.3 ● Chapter 2.7.3
5	<i>Some important aspects of climate appear not to have changed.</i> ● Chapter 2.2.2 ● Chapter 2.2.5 ● Chapter 2.7.3 ● Chapter 2.7.3

Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate system.

SPM Page	Cross-Reference: SPM Topic – Chapter Section
5	Chapeau: “Changes in climate occur ...” Chapter 1, Chapter 3.1, Chapter 4.1, Chapter 5.1, Chapter 6.1, 6.2, 6.9, 6.11 and 6.13
7	<i>Concentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities.</i> Carbon dioxide: ● Chapter 3.3.1, 3.3.2, 3.3.3 and 3.5.1 ● Chapter 3.5.1 ● Chapter 3.2.2, 3.2.3, 3.5.1 and Table 3.1 ● Chapter 3.5.1 and 3.5.2 Methane: ● Chapter 4.2.1 Nitrous oxide: ● Chapter 4.2.1 Halocarbons: ● Chapter 4.2.2 Radiative forcing of well-mixed gases: ● Chapter 4.2.1 and Chapter 6.3 Stratospheric ozone: ● Chapter 4.2.2 and Chapter 6.4 Tropospheric ozone: ● Chapter 4.2.4 and Chapter 6.5
9	<i>Anthropogenic aerosols are short-lived and mostly produce negative radiative forcing.</i> ● Chapter 5.2 and 5.5.4 ● Chapter 5.1, 5.2 and Chapter 6.7 ● Chapter 5.3.2, 5.4.3 and Chapter 6.8
9	<i>Natural factors have made small contributions to radiative forcing over the past century.</i> ● Chapter 6.11 and 6.15.1 ● Chapter 6.9 and 6.15.1 ● Chapter 6.15.1

Confidence in the ability of models to project future climate has increased.

SPM Page	Cross-Reference: SPM Topic – Chapter Section
9	Chapeau: “Complex physically-based ...” Chapter 8.3.2, 8.5.1, 8.6.1, 8.10.3 and Chapter 12.3.2
9	● Chapter 7.2.1, 7.5.2 and 7.6.1 ● Chapter 8.4.2 ● Chapter 8.6.3 and Chapter 12.3.2 ● Chapter 8.5.5, 8.7.1 and 8.7.5

There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.

SPM Page	Cross-Reference: SPM Topic – Chapter Section
10	Chapeau: “The SAR concluded: The balance of evidence suggests ...” Chapter 12.1.2 and 12.6
10	● Chapter 12.2.2, 12.4.3 and 12.6 ● Chapter 12.4.1, 12.4.2, 12.4.3 and 12.6 ● Chapter 12.2.3, 12.4.1, 12.4.2, 12.4.3 and 12.6 ● Chapter 12.4.3 and 12.6. ● Chapter 12.6 ● Chapter 12.4.3 ● Chapter 12.4.3 and 12.6
10	“In the light of new evidence and taking into account the ...” Chapter 12.4 and 12.6
10	“Furthermore, it is very likely that the 20th century warming has ...” Chapter 11.4

Human influences will continue to change atmospheric composition throughout the 21st century.

SPM Page	Cross-Reference: SPM Topic – Chapter Section
12	Chapeau: “Models have been used to make projections ...” Chapter 4.4.5 and Appendix II
12	<i>Greenhouse gases</i> ● Chapter 3.7.3 and Appendix II ● Chapter 3.7.1, 3.7.2, 3.7.3 and Appendix II ● Chapter 3.7.3 and Appendix II ● Chapter 3.2.2 and Appendix II ● Chapter 4.4.5, 4.5, 4.6 and Appendix II ● Chapter 3.7.3
12	<i>Aerosols</i> ● Chapter 5.5.2, 5.5.3 and Appendix II
12	<i>Radiative forcing over the 21st century</i> ● Chapter 6.15.2 and Appendix II

Global average temperature and sea level are projected to rise under all IPCC SRES scenarios.

SPM Page	Cross-Reference: SPM Topic – Chapter Section
13	<i>Temperature</i> ● Chapter 9.3.3 ● Chapter 9.3.3 ● Chapter 2.2.2, 2.3.2 and 2.4 ● Chapter 9.3.3 and Chapter 10.3.2 ● Chapter 8.6.1, Chapter 12.4.3, Chapter 13.5.1 and 13.5.2 ● Chapter 10.3.2 and Box 10.1 ● Chapter 9.3.2
13	<i>Precipitation</i> ● Chapter 9.3.1, 9.3.6, Chapter 10.3.2 and Box 10.1
15	<i>Extreme events</i> Table 1: Chapter 2.1, 2.2, 2.5, 2.7.2, 2.7.3, Chapter 9.3.6 and Chapter 10.3.2 ● Chapter 2.7.3 and Chapter 9.3.6
16	<i>El Niño</i> ● Chapter 9.3.5 ● Chapter 9.3.5
16	<i>Monsoons</i> ● Chapter 9.3.5
16	<i>Thermohaline circulation</i> ● Chapter 9.3.4
16	<i>Snow and ice</i> ● Chapter 9.3.2 ● Chapter 11.5.1 ● Chapter 11.5.1 ● Chapter 11.5.4
16	<i>Sea level</i> ● Chapter 11.5.1

Anthropogenic climate change will persist for many centuries.

SPM Page	Cross-Reference: SPM Topic – Chapter Section
17	● Chapter 3.2.3, Chapter 4.4 and Chapter 6.15 ● Chapter 9.3.3 and 9.3.4 ● Chapter 11.5.4 ● Chapter 11.5.4 ● Chapter 11.5.4

Further work is required to address remaining gaps in information and understanding.

SPM Page	Cross-Reference: SPM Topic – Chapter Section
17 – 18	All bullet points: Chapter 14, Executive Summary