CHAPTER 2

Weather and climate: changing human exposures

K. L. Ebi,[1] L. O. Mearns,[2] B. Nyenzi[3]

Introduction

Research on the potential health effects of weather, climate variability and climate change requires understanding of the exposure of interest. Although often the terms weather and climate are used interchangeably, they actually represent different parts of the same spectrum. Weather is the complex and continuously changing condition of the atmosphere usually considered on a time-scale from minutes to weeks. The atmospheric variables that characterize weather include temperature, precipitation, humidity, pressure, and wind speed and direction. Climate is the average state of the atmosphere, and the associated characteristics of the underlying land or water, in a particular region over a particular time-scale, usually considered over multiple years. Climate variability is the variation around the average climate, including seasonal variations as well as large-scale variations in atmospheric and ocean circulation such as the El Niño/Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO). Climate change operates over decades or longer time-scales. Research on the health impacts of climate variability and change aims to increase understanding of the potential risks and to identify effective adaptation options.

Understanding the potential health consequences of climate change requires the development of empirical knowledge in three areas (*1*):

1. historical analogue studies to estimate, for specified populations, the risks of climate-sensitive diseases (including understanding the mechanism of effect) and to forecast the potential health effects of comparable exposures either in different geographical regions or in the future;
2. studies seeking early evidence of changes, in either health risk indicators or health status, occurring in response to actual climate change;
3. using existing knowledge and theory to develop empirical-statistical or biophysical models of future health outcomes in relation to defined climate scenarios of change.

The exposures of interest in these studies may lie on different portions of the weather/climate spectrum. This chapter provides basic information to understand weather, climate, climate variability and climate change, and then discusses some analytical methods used to address the unique challenges presented when studying these exposures.

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[1] World Health Organization Regional Office for Europe, European Centre for Environment and Health, Rome, Italy.

[2] National Center for Atmospheric Research, Boulder, CO, USA.

[3] World Climate Programme, World Meteorological Organization, Geneva, Switzerland.

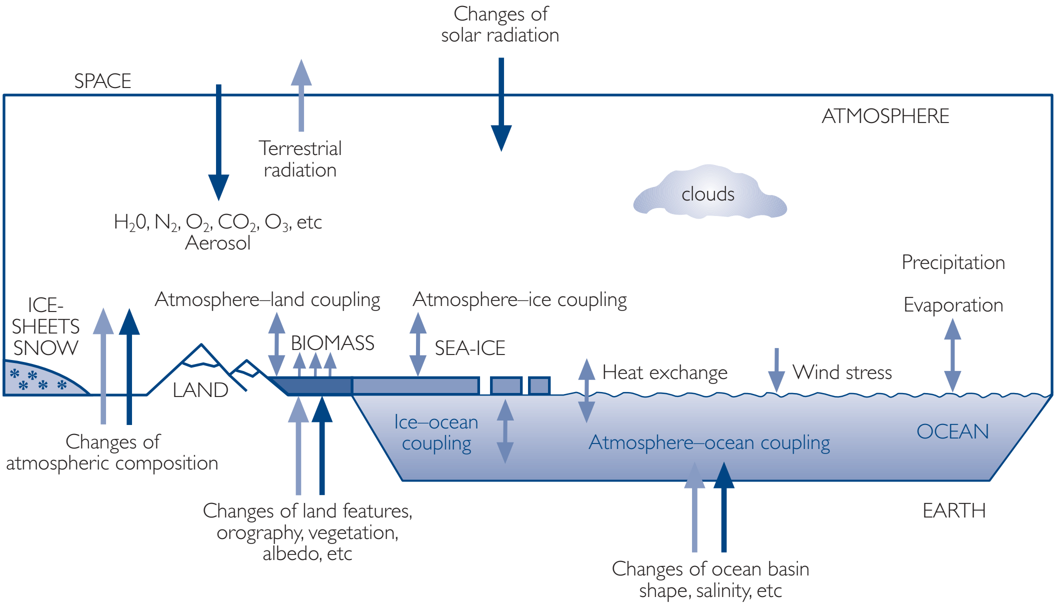
The climate system and greenhouse gases

Earth's climate is determined by complex interactions among the Sun, oceans, atmosphere, cryosphere, land surface and biosphere (shown schematically in Figure 2.1). These interactions are based on physical laws (conservation of mass, conservation of energy and Newton's second law of motion). The Sun is the principal driving force for weather and climate. The Sun's energy is distributed unevenly on Earth's surface due to the tilt of Earth's axis of rotation. Over the course of a year, the angle of rotation results in equatorial areas receiving more solar energy than those near the poles. As a result, the tropical oceans and land masses absorb a great deal more heat than the other regions of Earth. The atmosphere and oceans act together to redistribute this heat. As the equatorial waters warm air near the ocean surface, it expands, rises (carrying heat and moisture with it) and drifts towards the poles; cooler denser air from the subtropics and the poles moves toward the equator to take its place.

This continual redistribution of heat is modified by the planet's west to east rotation and the Coriolis force associated with the planet's spherical shape, giving rise to the high jet streams and the prevailing westerly trade winds. The winds, in turn, along with Earth's rotation, drive large ocean currents such as the Gulf Stream in the North Atlantic, the Humboldt Current in the South Pacific, and the North and South Equatorial Currents. Ocean currents redistribute warmers waters away from the tropics towards the poles. The ocean and atmosphere exchange heat and water (through evaporation and precipitation), carbon dioxide and other gases. By its mass and high heat capacity, the ocean moderates climate change from season to season and year to year. These complex, changing atmospheric and oceanic patterns help determine weather and climate.

Five layers of atmosphere surround Earth, from surface to outer space. The lowest layer (troposphere) extends from ground level to 8–16 km. The height

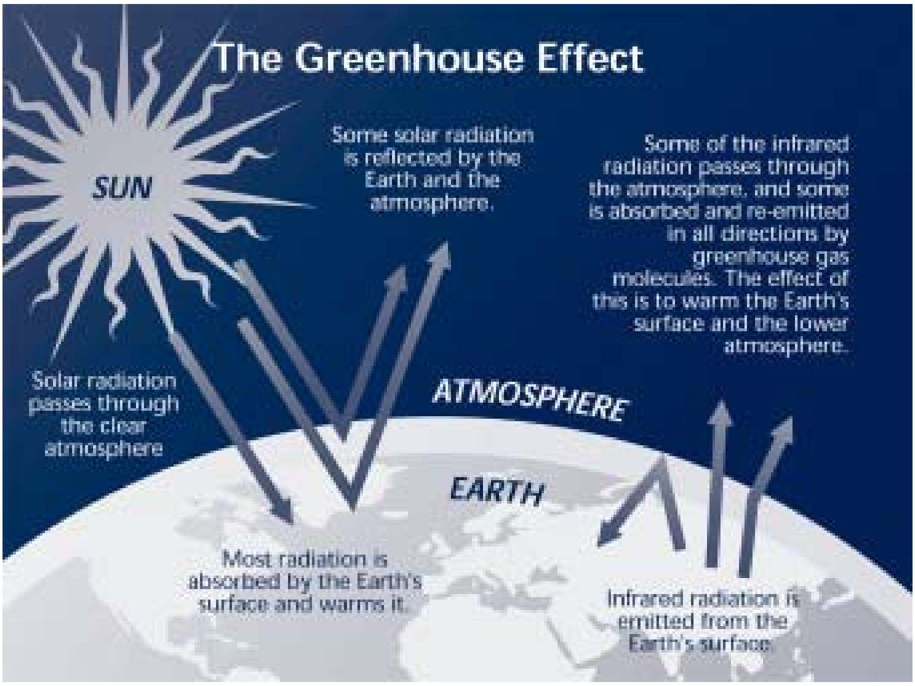
FIGURE 2.1 Schematic illustration of the components of the coupled atmosphere/earth /ocean system. *Source: reproduced from reference 2.*



varies with the amount of solar energy reaching Earth; it is lowest at the poles and highest near the equator. On average, air temperature in the troposphere decreases 7 °C for each kilometre increase in altitude, as atmospheric pressure decreases. The troposphere is the level where the weather that affects the surface of Earth develops. The level at which temperature stops decreasing with height is called the tropopause, and temperatures here can be as low as −58 °C. The next layer (stratosphere) extends from the tropopause to about 50 km above the surface, with temperatures slowly increasing to about 4 °C at the top. A high concentration of ozone occurs naturally in the stratosphere at an altitude of about 24 km. Ozone in this region absorbs most of the Sun's ultraviolet rays that would be harmful to life on Earth's surface. Above the stratosphere are three more layers (mesosphere, thermosphere and exosphere) characterized by falling, then rising, temperature patterns.

Overall, the atmosphere reduces the amount of sunlight reaching Earth's surface by about 50%. Greenhouse gases (including water vapour, carbon dioxide, nitrous oxide, methane, halocarbons, and ozone) compose about 2% of the atmosphere. In a clear, cloudless atmosphere they absorb about 17% of the sunlight passing through it (*3*). Clouds reflect about 30% of the sunlight falling on them and absorb about 15% of the sunlight passing through them. Earth's surface absorbs some sunlight and reradiates it as long-wave (infrared) radiation. Some of this infrared radiation is absorbed by atmospheric greenhouse gases and reradiated back to Earth, thereby warming the surface of Earth by more than would be achieved by incoming solar radiation alone. This atmospheric greenhouse effect is the warming process that raises the average temperature of Earth to its present 15 °C (Figure 2.2). Without this warming, Earth's diurnal temper-

FIGURE 2.2 The greenhouse effect. *Source: reproduced from reference 4.*



ature range would increase dramatically and the average temperature would be about 33 °C colder (*3*). Changes in the composition of gases in the atmosphere alter the intensity of the greenhouse effect. This analogy arose because these gases have been likened to the glass of a greenhouse that lets in sunlight but does not allow heat to escape. This is only partially correct—a real greenhouse elevates the temperature not only by the glass absorbing infrared radiation, but also by the enclosed building dramatically reducing convective and advective losses from winds surrounding the building. Yet the misnomer persists.

For Earth as a whole, annual incoming solar radiation is balanced approximately by outgoing infrared radiation. Climate can be affected by any factor that alters the radiation balance or the redistribution of heat energy by the atmosphere or oceans. Perturbations in the climate system that cause local to global climate fluctuations are called forcings. This is short for radiative forcing which can be considered a perturbation in the global radiation (or energy) balance due to internal or external changes in the climate system. Some forcings result from natural events: occasional increases in solar radiation make Earth slightly warmer (positive forcing), volcanic eruptions into the stratosphere release aerosols that reflect more incoming solar radiation causing Earth to cool slightly (negative forcing). Characterization of these forcing agents and their changes over time is required to understand past climate changes in the context of natural variations and to project future climate changes. Other factors, such as orbital fluctuations and impacts from large meteors, also influenced past natural climate change.

Anthropogenic forcing results from the gases and aerosols produced by fossil fuel burning and other greenhouse gas emission sources, and from alterations in Earth's surface from various changes in land use, such as the conversion of forests into agricultural land. Increases in the concentrations of greenhouse gases will increase the amount of heat in the atmosphere. More outgoing terrestrial radiation from the surface will be absorbed, resulting in a positive radiative forcing that tends to warm the lower atmosphere and Earth's surface. The amount of radiative forcing depends on the size of the increase in concentration of each greenhouse gas and its respective radiative properties (*5*).

The usual unit of measure for climatic forcing agents is the energy perturbation introduced into the climate system (measured in watts per square metre). A common way of representing the consequences of such forcings for the climate system is in the change in average global temperature. The conversion factor from forcing to temperature change is the sensitivity of the climate system (*5*). This sensitivity is commonly expressed in terms of the global mean temperature change that would be expected after a time sufficient for both atmosphere and ocean to come to equilibrium with the change in climate forcing. Climate feedbacks influence climate sensitivity; the responses of atmospheric water vapour concentration and clouds probably generate the most important feedbacks (*6*). The nature and extent of these feedbacks give rise to the largest source of uncertainty about climate sensitivity.

When radiative forcing changes (positively or negatively), the climate system responds on various time-scales (*5*). The longest may last for thousands of years because of time lags in the response of the cryosphere (e.g. sea ice, ice sheets) and deep oceans. Changes over short (weather) time-scales are due to alterations in the global hydrological cycle and short-lived features of the atmosphere such as locations of storm tracks, weather fronts, blocking events and tropical cyclones, which affect regional temperature and precipitation patterns. Greenhouse gases that contribute to forcing include: water vapour, carbon dioxide, nitrous oxide, methane and ozone. Aerosols released in fossil fuel burning also influence climate by reflecting solar radiation.

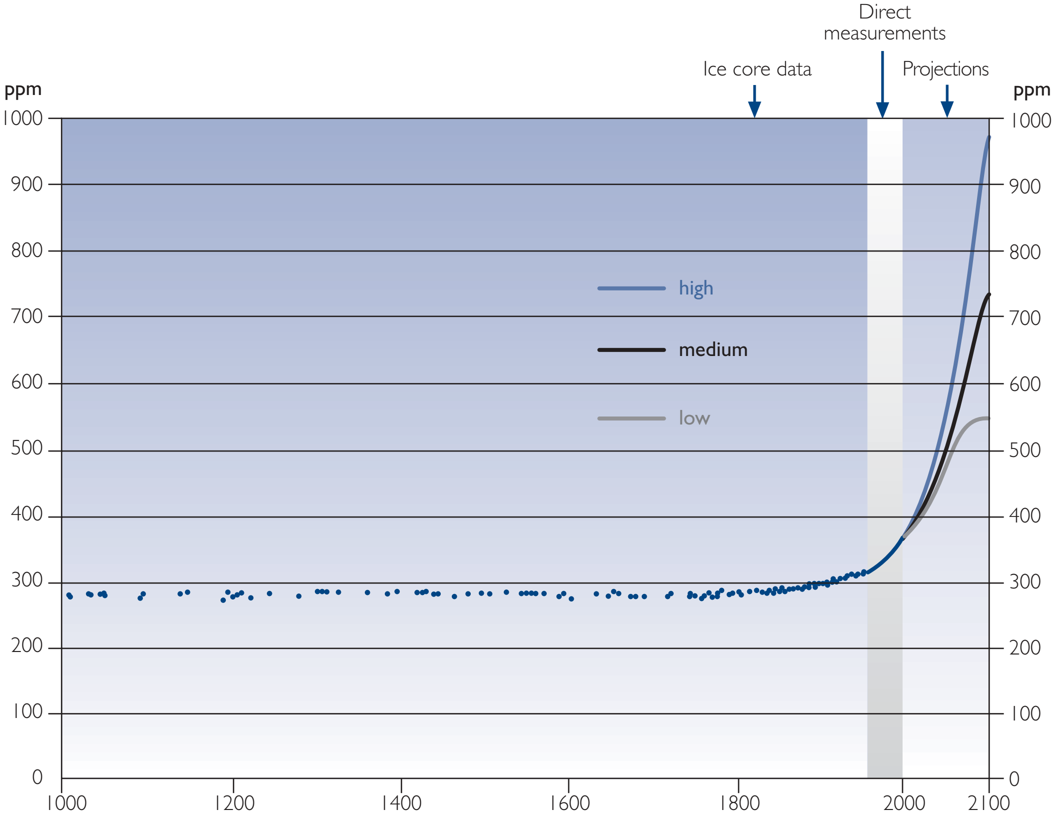
In addition to adding greenhouse gases and aerosols to the atmosphere, other anthropogenic activities affect climate on local and regional scales. Changes in land use and vegetation can affect climate over a range of spatial scales. Vegetation affects a variety of surface characteristics such as albedo (reflectivity) and roughness (vegetation height), as well as other aspects of the energy balance of the surface through evapotranspiration. Regional temperature and precipitation can be influenced because of changes in vegetation cover. A modelling study by Pielke et al. estimated that loss of vegetation in the South Florida Everglades over the last century decreased rainfall in the region by about 10% (*7*). Bonan demonstrated that the conversion of forests to cropland in the United States resulted in a regional cooling of about 2 °C (*8*). There is concern that deforestation induced drought may be occurring in the Amazon and other parts of the tropics (*9*). However, recent evidence suggests that deforestation and interannual climate fluctuations interact in a non-linear manner such that the response of Amazon rainfall to deforestation also depends on the phase of the El Niño/Southern Oscillation (ENSO) cycle (*10*). In some transition regions there may be more, not less, precipitation from deforestation. Another land-use impact is the urban heat island wherein cities can be up to 12 °C warmer than surrounding areas due to the extra heat absorbed by asphalt and concrete, and by the relative lack of vegetation to promote evaporative cooling (*6*).

Water vapour is the major greenhouse gas, contributing a positive forcing ten times greater than that of the other gases. Clouds (condensed water) produce both positive and negative forcing: positive by trapping Earth's outgoing radiation at night, and negative by reflecting sunlight during the day. Understanding how to measure accurately and simulate cloud effects remains one of the most difficult tasks for climate science.

Carbon dioxide currently contributes the largest portion of anthropogenic positive forcing. Atmospheric CO_2 is not destroyed chemically and its removal from the atmosphere occurs through multiple processes that transiently store the carbon in the land and ocean reservoirs, and ultimately in mineral deposits (*5*). A major removal process depends on the transfer of the carbon content of near-surface waters to the deep ocean, on a century time-scale, with final removal stretching over hundreds of thousands of years. Natural processes currently remove about half the incremental man-made CO_2 added to the atmosphere each year; the balance can remain in the atmosphere for more than 100 years (*6*). Atmospheric concentrations of CO_2 have increased by 31% since 1750 (*5*). Current global concentrations average about 370 ppmv (parts per million by volume). This concentration has not been exceeded during the past 420 000 years and probably not during the past 20 million years (*3*). Measurements begun in the 1950s show that atmospheric CO_2 has been increasing at about 0.5% per year (Figure 2.3). This rate of increase is unprecedented during at least the past 20 000 years (*5*). About 75% of the anthropogenic CO_2 emissions to the atmosphere during the past 20 years were due to fossil fuel burning (*5*). Much of the rest were due to land-use change, especially deforestation.

Methane (CH_4) contributes a positive forcing about half that of CO_2 (*5*). It is released from cultivating rice; raising domestic ruminants (cows, sheep); disposing waste and sewage in landfills; burning biomass; and operating leaking gas pipelines. The atmospheric concentration of methane has increased 151% since 1750 (*5*). Measurements between the early 1980s and 2000 showed a 10%

FIGURE 2.3 Observed and projected atmospheric CO_2 concentrations from 1000 to 2100. From ice core data and from direct atmospheric measurements over the past few decades. Projections of CO_2 concentrations for the period 2000–2100 are based on the IS92a scenario (medium), and the highest and lowest of the range of SRES scenarios. *Source: reproduced from reference 11.*



increase in atmospheric CH_4 to 1850 ppb (parts per billion). Although the rate of increase has slowed to near zero in the past two years, present CH_4 concentrations have not been exceeded during the past 420 000 years. CH_4 remains in the atmosphere about 10 years. The primary removal mechanism is by chemical reaction in the stratosphere with hydroxyl ions to produce carbon dioxide and water vapour.

Other greenhouse gases include nitrous oxide and ozone. Nitrous oxide is emitted by both natural and anthropogenic sources, and removed from the atmosphere by chemical reactions. The atmospheric concentration of nitrous oxide has increased steadily since the Industrial Revolution and is now about 16% larger than in 1750 (*5*). Nitrous oxide has a long atmospheric lifetime.

Ozone (O_3) is not emitted directly but formed from photochemical processes involving both natural and anthropogenic species. Ozone remains in the atmosphere for weeks to months. Its role in climate forcing depends on altitude: in the upper troposphere it contributes a small positive forcing, while in the stratosphere it caused negative forcing over the past two decades (*5*). Based on limited observations, global tropospheric ozone has increased by about 35% since pre-industrial times.

TABLE 2.1 Examples of greenhouse gases that are affected by human activities.

	CO_2 (Carbon Dioxide)	CH_4 (Methane)	N_2O (Nitrous Oxide)	CFC-11 (chlorofluoro-carbon-11)	HFC-23 (Hydrofluoro-carbon-23)	CF_4 (Perfluoromethane)
Pre-industrial concentration	~280 ppm	~700 ppb	~270 ppb	Zero	Zero	40 ppt
Concentration in 1998	365 ppm	1745 ppb	314 ppb	268 ppt	14 ppt	80 ppt
Rate of Concentration change[b]	1.5 ppm/yr[a]	7.0 ppb/yr[a]	0.8 ppb/yr	–1.4 ppt/yr	0.55 ppt/yr	1 ppt/yr
Atmospheric lifetime	5–200 yr[c]	12yr[d]	114 yr[d]	45 yr	260 yr	>50,000 yr

[a] Rate has fluctuated between 0.9 ppm/yr and 2.8 ppm/yr for CO_2 and between 0 and 13 ppb/yr for CH_4 over the period 1990 to 1999.

[b] Rate is calculated over the period 1990 to 1999.

[c] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.

[d] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

Source: reproduced from reference 5.

Aerosols are microscopic particles or droplets in air, their major anthropogenic sources are fossil fuel and biomass burning. They can reflect solar radiation and can alter cloud properties and lifetimes. Depending on their size and chemistry, aerosols contribute either positive or negative forcing. For example, sulphate particles scatter sunlight and cause cooling. Soot (black carbon particles) can warm the climate system by absorbing solar radiation. Aerosols have a lifetime of days to weeks and so respond fairly quickly to changes in emissions. They are less well measured than greenhouse gases.

Table 2.1 provides examples of several greenhouse gases and summarizes their 1790 and 1998 concentrations; rate of change over the period 1990–1999; and atmospheric lifetime. The atmospheric lifetime is highly relevant to policymakers because emissions of gases with long lifetimes is a quasi-irreversible commitment to sustained positive forcing over decades, centuries or millennia (*3*).

Weather, climate and climate variability

The terms weather and climate often are used interchangeably, but they actually represent different parts of the same spectrum. Weather is the day-to-day changing atmospheric conditions. Climate is the average state of the atmosphere and the underlying land or water in a particular region over a particular time-scale. Put more simply, climate is what you expect and weather is what you get. Climate variability is the variation around the mean climate; this includes seasonal variations and irregular events such as the El Niño/Southern Oscillation. These differences amongst weather, climate and climate variability have not been applied consistently across studies of potential health impacts, which can lead to confusion and/or misinterpretation.

Elements of daily weather operate on a variety of scales. Well-defined patterns dominate the distribution of atmospheric pressure and winds across Earth. These large-scale patterns are called the general circulation. Smaller patterns are found on the synoptic scale, on the order of hundreds or thousands of square kilometres. Synoptic scale features (e.g. cyclones, troughs and ridges) persist for a period of days to as much as a couple of weeks. Other elements of daily weather operate at the mesoscale, which is on the order of tens of square kilometres, and for periods as brief as half an hour. The smallest scale at which heat and moisture transfers occur is the microscale, such as across the surface of a single leaf.

Climate is typically described by the summary statistics of a set of atmospheric and surface variables such as: temperature, precipitation, wind, humidity, cloudiness, soil moisture, sea surface temperature, and the concentration and thickness of sea ice. The official average value of a meteorological element for a specific location over 30 years is defined as a climate normal (*12*). Included are data from weather stations meeting quality standards prescribed by the World Meteorological Organization. Climate normals are used to compare current conditions and are calculated every 10 years.

Climatologists use climatic normals as a basis of comparison for climate during the following decade. Comparison of normals between 30-year periods may lead to erroneous conclusions about climatic change due to changes over the decades in station location, instrumentation used, methods of weather observations and how the various normals were computed (*12*). The differences between normals due to these primarily anthropogenically-induced changes may be larger than those due to a true change in climate.

The climate normal for the 1990s was the period 1961–1990. This was the baseline for the analyses of climatic trends summarized by the IPCC Third Assessment Report. In January 2002, the climate normal period changed to 1971–2000. This change in the climate normal means a change in the baseline of comparison; different conclusions may result when comparisons are made using different baselines.

A climate normal is simply an average and therefore does not completely characterize a particular climate. Some measure of the variability of the climate also is desirable. This is especially true for precipitation in dry climates, and with temperatures in continental locations that frequently experience large swings from cold to warm air masses. Typical measures of variability include the standard deviation and interquartile range. Some measures of the extremes of the climate are useful also.

A variety of organizations and individuals summarize weather over various temporal and spatial scales to create a picture of the average meteorological conditions in a region. There are well-known spatial latitudinal and altitudinal temperature gradients. For example, under typical conditions in mountainous terrain, the average surface air or soil temperature decreases by about 6.5 °C for every 1000 m increase in elevation, and along an equator to pole gradient a distance of 1000 km corresponds to an average surface temperature change of about 5 °C (*6*). Superimposed on these large-scale gradients are more complex regional and local patterns.

Temporal climate variations are most obviously recognized in normal diurnal and seasonal variations. The amplitude of the diurnal temperature cycle at most locations is typically in the range of 5–15 °C (*3*). The amplitude of seasonal variability is generally larger than that of the diurnal cycle at high latitudes and smaller at low latitudes. Years of research on seasonal to interannual variations have uncovered several recurring pressure and wind patterns that are termed modes of climate variability (*6*).

The El Niño/Southern Oscillation (ENSO) cycle is one of Earth's dominant modes of climate variability. ENSO is the strongest natural fluctuation of climate on interannual time-scales, with global weather consequences (*13*, *14*). An El Niño event occurs approximately every two to seven years. Originally the term applied only to a warm ocean current that ran southwards along the coast of Peru about Christmas time. Subsequently an atmospheric component, the Southern Oscillation, was found to be connected with El Niño events. The atmosphere and ocean interact to create the ENSO cycle: there is a complex interplay between the strength of surface winds that blow westward along the equator and subsurface currents and temperatures (*13*). The ocean and atmospheric conditions in the tropical Pacific fluctuate somewhat irregularly between El Niño and La Niña events (which consist of cooling in the tropical Pacific) (*15*). The most intense phase of each event usually lasts about one year.

Worldwide changes in temperature and precipitation result from changes in sea surface temperature during the ENSO cycle (*14*, *16*). During El Niño events, abnormally heavy rainfall occurs along part of the west coast of South America, while drought conditions often occur in parts of Australia, Malaysia, Indonesia, Micronesia, Africa, north-east Brazil and Central America (*13*). These changes can have a strong effect on the health of individuals and populations because of associated droughts, floods, heatwaves and changes that can disrupt food production (*16*). Predictions of ENSO associated regional anomalies (deviations or departures from the normal) are generally given in probabilistic terms because the likelihood of occurrence of any projected anomaly varies from one region to another, and with the strength and specific configuration of the equatorial Pacific sea surface temperature anomalies (*12*).

ENSO is not the only mode of climate variability. The Pacific Decadal Oscillation (PDO) and the North Atlantic–Artic Oscillation (NAO–AO) are well established as influences on regional climate. The NAO is a large-scale oscillation in atmospheric pressure between the subtropical high near the Azores and the sub-polar low near Iceland (*17*). The latter appears to have a particularly large decadal signal (*18*). The PDO signal may fluctuate over several decades.

A note about terminology used by meteorologists and climatologists is relevant. The terms forecast and prediction each refer to statements about future events: predictions are statements that relate to the results of a single numerical model; forecasts are statements that relate to a synthesis of a number of predictions (*6*). Forecasts and predictions are currently most relevant to future (i.e. near-term) weather conditions and seasonal climate conditions. Estimates of long-term climate change usually are discussed in terms of projections, which are less certain than predictions or forecasts. Projections (of future climate) are based on estimates of possible future changes with no specific probability attached to them.

Climate change

Climate change operates over decades or longer. Changes in climate occur as a result of both internal variability within the climate system and external factors (both natural and anthropogenic). The climate record clearly shows that climate is always changing (Figure 2.4). One feature of the record is that climate over the past 10 000 years has been both warm and relatively stable (*5*).

Past changes could not be observed directly, but are inferred through a variety of proxy records such as ice cores and tree rings. Such records can be used to make inferences about climate and atmospheric composition extending back as far as 400 000 years. These data indicate that the range of natural climate variability is in excess of several degrees Celsius on local and regional spatial scales over periods as short as a decade (*5*). Precipitation also has varied widely.

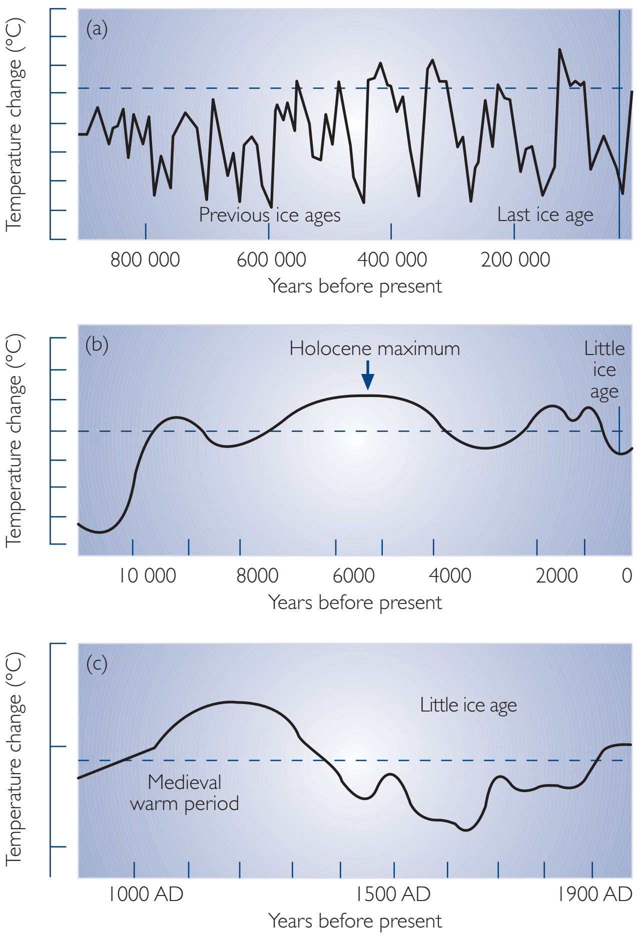


FIGURE 2.4 Schematic diagrams of global temperature variations since the Pleistocene on three time-scales: (a) last million years (b) last 10 000 years (c) last 1000 years. The dotted line nominally represents conditions near the beginning of the century. *Source: reproduced from reference 19.*

On century to millennial scales, climate changes such as the European 'little ice age' from the fourteenth to eighteenth centuries occur (*20*). Over the past approximately million years, the global climate record is characterized by larger glacial-interglacial transitions, with multiple periodicities of roughly 20 000, 40 000 and 100 000 years (*6*). These are correlated with the effects of Earth-Sun orbital variations. The amplitudes of these transitions are on the order of 5–10 °C and are accompanied by large extensions and retreats of polar and glacial ice.

In 1861, instrumental records began recording temperature, precipitation and other weather elements. Figure 2.5 shows the annual global temperature (average of near surface air temperature over land and of sea surface temperatures) expressed as anomalies or departures from the 1961 to 1990 baseline. Over the twentieth century, the global average surface temperature increased about 0.6 °C ± 0.2 °C, the 1990s being the warmest decade and 1998 the warmest year in the Northern Hemisphere (*5*). The high global temperatures associated with the 1997–1998 El Niño event are apparent, even taking into account recent warming trends. The increase in temperature over the twentieth century is likely to have been the largest of any century during the past 1000 years (Figure 2.6) (*5*). The warmth of the 1990s was outside the 95% confidence interval of temperature uncertainty, defined by historical variation, during even the warmest periods of the last millennium (*3*).

FIGURE 2.5 Combined annual land-surface, air, and sea surface temperature anomalies (°C) from 1861 to 2000, relative to 1961 to 1990. *Source: produced from data from reference 21.*

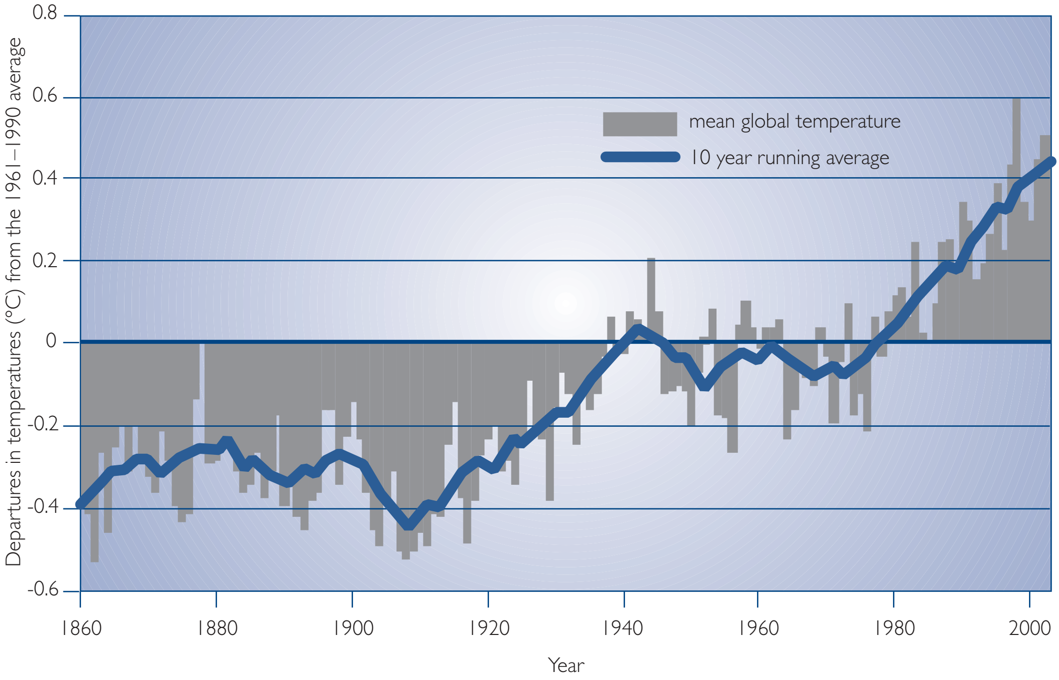
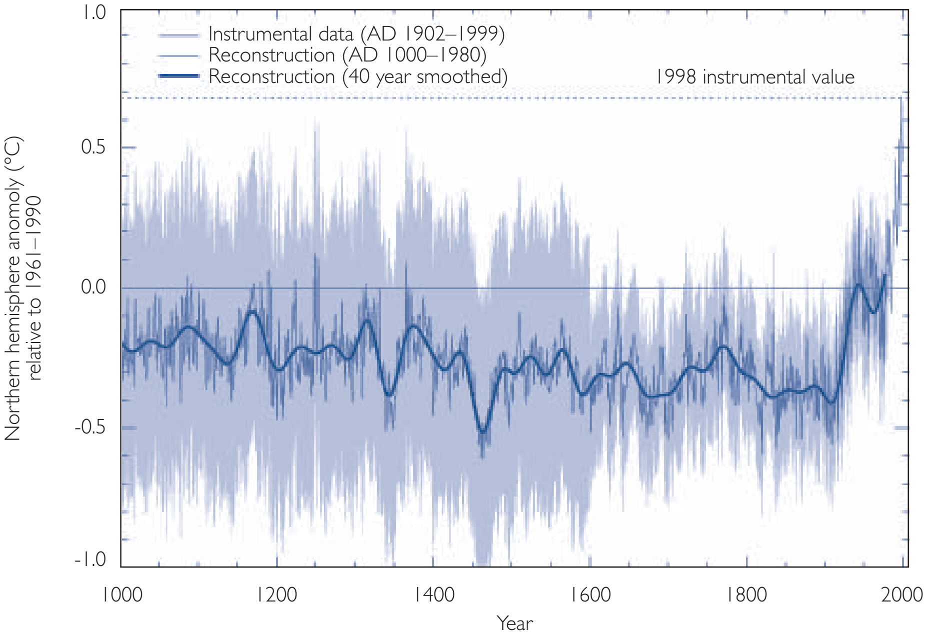


FIGURE 2.6 Millennial Northern Hemisphere (NH) temperature reconstruction from AD 1000 to 1999. Measurements before the 1850s are based on tree rings, corals, ice cores, and historical records. Later records are from instrumental data. The dark line is a smoother version of the series and the shaded area represents two standard error limits. *Source: reproduced from reference 5.*



The regional patterns of warming that occurred in the early twentieth century differ from those of the latter part (*5*). The largest increases in temperature occurred over the mid and high latitudes of the continents in the Northern Hemisphere. Regional temperature patterns are related, in part, to various phases of atmospheric-oceanic oscillations, such as the North Atlantic–Artic Oscillation (*5*). Regional temperature patterns over a few decades can be influenced strongly by regional climate variability, causing a departure from global trends. More time must elapse before the importance of recent temperature trends can be assessed. However, the Northern Hemisphere temperatures of the 1990s were warmer than any other time in the past six to ten centuries (*5*). Less is known about the conditions that prevailed in the Southern Hemisphere prior to 1861 because limited data are available.

Climate variability and change over the twentieth century

In the Third Assessment Report of the Intergovernmental Panel on Climate Change, Working Group I summarized climatic changes that occurred over the twentieth century. A concerted effort was made to express the uncertainty about climate trends in a consistent and meaningful fashion. Thus, confidence in their judgements was expressed as: virtually certain (>99% chance that a result is true); very likely (90–99% chance); likely (66–90% chance); medium likely (33–66% chance); unlikely (10–33% chance); and very unlikely (1–10% chance) (*5*). This terminology is used in the summary below.

On average, between 1950 and 1993, night time daily minimum air temperatures over land increased by about 0.2 °C per decade, although this did not happen everywhere (*5*). This increase may be due to a likely increase in cloud cover of about 2% since the beginning of the twentieth century (*5*). This increase was about twice the rate of increase in daytime daily maximum air temperatures (0.1 °C per decade) and lengthened the freeze-free season in many mid and high latitude regions.

Along with these temperature changes, snow cover and ice extent decreased. Snow cover has very likely decreased about 10% since the late 1960s, and spring and summer sea ice extent decreased about 10–15% since the 1950s. There is now ample evidence to support a major retreat of alpine and continental glaciers in response to twentieth century warming. However, in a few maritime regions, increases in precipitation overshadowed increases in temperature in the past two decades, and glaciers re-advanced (*5*). Sea ice is important because it reflects more incoming solar radiation than the sea surface and insulates the sea from heat loss. Therefore, reduction of sea ice causes positive climate forcing at high latitudes.

Data show that global average sea level rose between 0.1 and 0.2 m during the twentieth century. Based on tide gauge data, the rate of global mean sea level rise was in the range of 1.0 to 2.0 mm per year, compared to an average rate of about 0.1 to 0.2 mm per year over the last 3000 years (*5*). This does not mean that sea level is rising in all areas: the retreat of glacial ice in the past several thousand years has lead to a rebound of land in some areas. Sea level has been rising for several reasons. First, ocean water expands as it warms. On the basis of observations and model results, thermal expansion is one of the major contributors to historical sea level changes (*5*). Thermal expansion is expected to be the largest contributor to sea level rise over the next 100 years. As deep ocean temperatures change slowly, thermal expansion is expected to continue for many centuries after stabilization of greenhouse gases. Second, after thermal expansion, the melting of mountain glaciers and ice caps is expected to make the next largest contribution to sea level rise over the next 100 years. These glaciers and ice caps are much smaller than the large ice sheets of Greenland and Antarctica, and are more sensitive to climate change. Third, processes unrelated to climate change influence sea level; these processes could have regional effects on sea level, such as coastal subsidence in river delta regions.

Other changes include the following:

- it is very likely that precipitation increased by 0.5–1.0% per decade over most mid and high latitudes of the Northern Hemisphere continents, and likely that rainfall increased 0.2–0.3% per decade over tropical land areas. Also it is likely that rainfall decreased over much of the Northern Hemisphere subtropical land areas. Comparable systematic changes were not detected over the Southern Hemisphere;
- it is likely that there was a 2–4% increase in the frequency of heavy precipitation events in mid and high latitudes of the Northern Hemisphere over the latter half of the twentieth century;
- since 1950, it is very likely that there was a reduction in the frequency of extremely low temperatures, with a smaller increase in the frequency of extreme high temperatures;
- El Niño events were more frequent, persistent and intense since the mid-1970s, compared with the previous 100 years;
- in parts of Asia and Africa, the frequency and intensity of droughts increased in recent decades.

However, not all aspects of climate changed during the last century (*5*). A few areas of the globe cooled 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. No systematic changes in the frequency of tornadoes or other severe storms are evident.

One area of concern is the possibility of a sudden, large change in the climate system in response to accumulated climatic forcing. The paleoclimate record contains examples of such changes, at least on regional scales.

Special Report on Emission Scenarios

The projection of future climate change first requires projection of future emissions of greenhouse gases and aerosols, for example, the future fossil fuel and land-use sources of CO_2 and other gases and aerosols. How much of the carbon from future use of fossil fuels will increase atmospheric CO_2 will depend on what fractions are taken up by land and the oceans. Future climate change depends also on climate sensitivity.

For the Third Assessment Report, the IPCC developed a series of scenarios that include a broad range of assumptions about future economic and technological development to encompass the uncertainty about the structure of society in 2100. These scenarios are called collectively the SRES, from the Special Report on Emission Scenarios (*22*). An earlier baseline, or business as usual, scenario (or IS92a) assumed rapid growth rates such that annual greenhouse gas emissions continue to accelerate; this scenario was developed for the Second Assessment Report. The SRES scenarios produce a range of emission projections that are both larger and smaller in 2100 than the IS92a scenario. The SRES scenarios are grouped into four narrative storylines. The storylines can be categorized basically in a 2x2 table, with the axes global versus regional focus, and a world focused more on consumerism versus a world focused more on conservation. The basic storylines are A1 (world markets), B1 (global sustainability), A2 (provincial enterprise) and B2 (local stewardship). Each storyline contains underlying assumptions about population growth, economic development, life style choices, technological change and energy alternatives. Each leads to different patterns and concentrations of emissions of greenhouse gases. In some storylines, the large growth in emissions could lead to degradation of the global environment in ways beyond climate change (*5*). No attempt was made to assign probabilities to the SRES scenarios; they are designed to illustrate a wide range of possible emissions outcomes. Much of the summary climate change information provided below is based on results from climate models that used the SRES scenarios.

Anthropogenic climate change

Several key questions are asked about climate change:

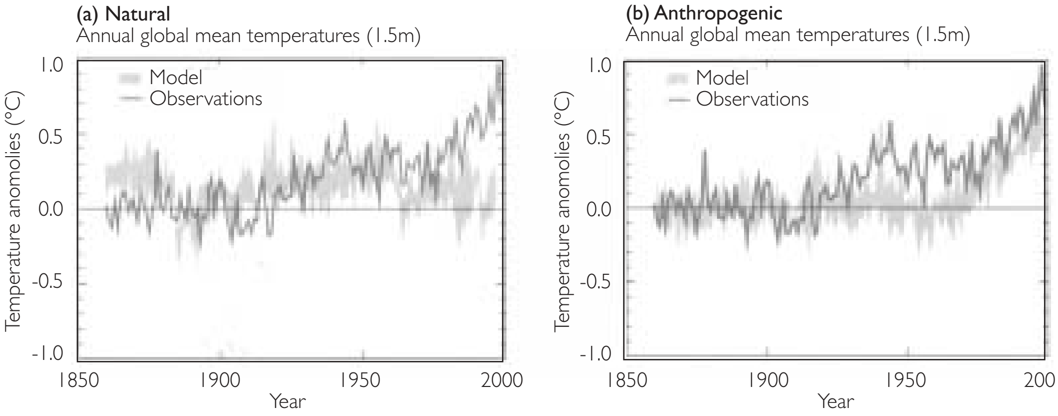
- was there detectable climate change during the twentieth century?
- if so, how much warming already experienced was likely to be due to human activities?
- how much additional warming is likely to occur if we increase the atmospheric levels of greenhouse gases?
- what will be the likely impacts?

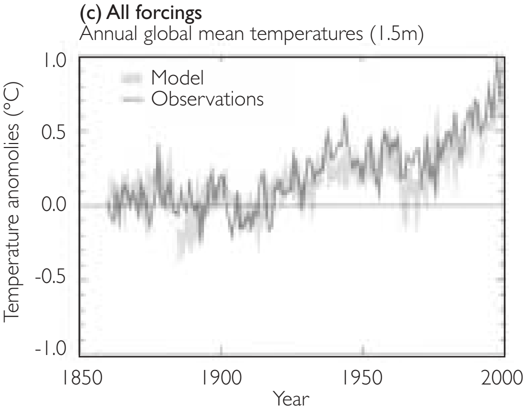
To distinguish anthropogenic climate changes from natural variation requires that the anthropogenic signal be identified against the noise of natural climate variability. The third question is important because the climate system has a great deal of inertia—changes to the atmosphere today may continue to affect the climate for decades or even centuries. Similarly, the consequences of efforts to reduce the magnitude of future change may not become apparent for decades to centuries. The question of impacts is addressed in other chapters in this book.

Two of the tasks of the IPCC's Third Assessment Report (TAR) were to determine whether there has been a detectable signal of climate change (in a statistical sense) and if so, to determine if any of the change could be attributed confidently to anthropogenic causes. One conclusion was that best agreement between observations and model simulations over the past 140 years was found when both natural factors and anthropogenic forcings were included in the models (Figure 2.7) (*5*). Further, the IPCC authors concluded that most of the warming observed over the past 50 years is attributable to human activities and that human influences will continue to change atmospheric composition throughout the twenty-first century (*5*). The IPCC authors concluded that emissions of CO_2 due to fossil fuel burning are virtually certain to be the dominant contributor to the trends in atmospheric CO_2 concentration throughout the twenty-first century.

By 2100, atmospheric concentrations of CO_2 are projected to be between 490 and 1260 ppm (75–350% above the concentration of 280 ppm in 1750) (*5*). Based on climate model results using the SRES scenarios, the IPCC projected that the global mean temperature of Earth would increase by the end of the twenty-first century by between 1.4 and 5.8 °C. Global precipitation also would increase. This projected rate of warming is much larger than the observed changes during the

FIGURE 2.7 Global mean surface temperature anomalies relative to the 1880 to 1920 mean from the instrumental record, compared with ensembles of four simulations with a coupled ocean-atmosphere climate model. The line shows the instrumental data while the shaded area shows the range of outputs from individual model simulations. Data are annual mean values. *Source: reproduced from reference 5.*

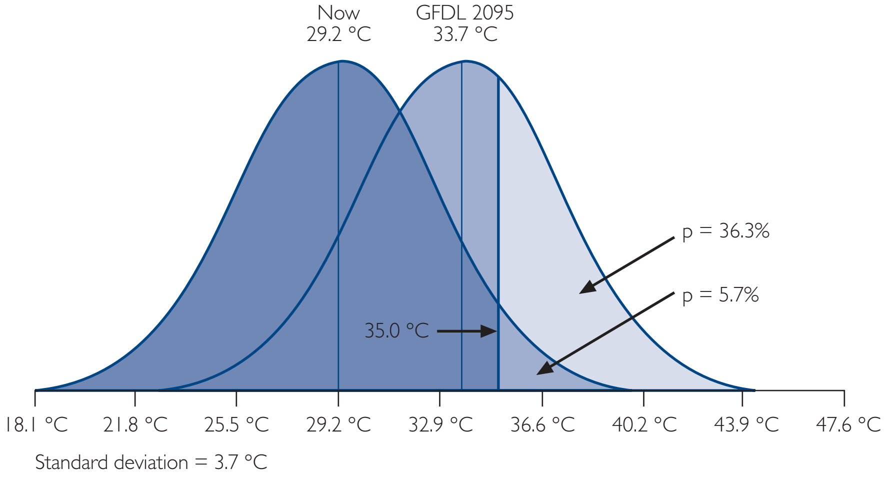




twentieth century and is very likely to be without precedent during at least the last 10000 years (*5*). These projections strongly depend on climate sensitivity. Recent publications, using different approaches and different models, conclude that these IPCC estimates are likely to be conservative (*23–25*). Andronova and Schlesinger concluded that there is a 54% likelihood that true climate sensitivity lies outside the IPCC range and that global average temperature increases could be higher or lower than those projected by the IPCC (*23*). Knutti et al. concluded that there is 40% probability that the warming could exceed that projected by the IPCC, and only 5% probability that it will be lower (*24*). In addition, these studies suggest that much of the warming over the next few decades will be due to past greenhouse gas emissions and thus relatively insensitive to mitigation efforts. Only beyond mid-century could mitigation efforts begin to affect global mean temperatures.

Average temperature increases are projected to be greatest in the northern regions of North America, and northern and central Asia. Precipitation also is projected to increase, particularly over the northern mid to high latitudes and

FIGURE 2.8 Distribution of July daily maximum temperatures in Chicago, today and in 2095 under one climate change scenario (GFDL). *Source: reproduced from reference 27.*



Antarctica in winter. Of particular note is that the shift in the mean of meteorological variables, such as temperature and precipitation, will result in a shift in extremes (Figure 2.8). For example, in Chicago, Illinois, currently about 6% of days in July and August are above 35 °C; under one climate scenario by 2095 that could rise to 36%. Global climate change is not likely to be spatially uniform and is expected to include changes in temperature and the hydrologic cycle. Associated health effects also will vary spatially. Higher evaporation rates will accelerate the drying of soils following rain events resulting in drier average conditions in some regions (*6*). Larger year-to-year variations in precipitation are very likely over most areas where an increase in mean precipitation is projected, including an increase in heavy rain events (*3*). Changes in other features of the climate system also could occur, for example the frequency and intensity of tropical and mid latitude storms. Global climate change may also influence the behaviour of ENSO or other modes of climate variability (*26*). Chapter 5 summarizes the health effects associated with El Niño events.

Between 1990 and 2100 global mean sea level is projected to rise 0.09–0.88 m (*5*, *28*). This will be due primarily to thermal expansion of the oceans and loss of mass from glaciers and ice caps. Sea levels are projected to continue rising for hundreds of years after stabilization of greenhouse gas concentrations due to the long time-scales on which the deep ocean adjusts to climate change.

Table 2.2 summarizes the confidence in observed changes in extremes of weather and climate during the latter part of the twentieth century and in projected changes during the twenty-first century.

Climate modelling

Projections of future climatic conditions are produced using climate system models. Atmosphere-Ocean general circulation models (AOGCMs) are mathematical expressions of the thermodynamics; fluid motions; chemical reactions; and radiative transfer of the complete climate system that are as comprehensive as allowed by computational feasibility and scientific understanding of their for-

TABLE 2.2 Estimates of confidence in observed and projected changes in extreme weather and climate events. The table 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 physical plausibility of future projections across all commonly used scenarios and is based on expert judgment. *Adapted from reference 5.*

Confidence in observed changes (latter half of the 20th century)	Changes in Phenomenon	Confidence in projected changes (during the 21st century)
Likely	Higher maximum temperatures and more hot days over nearly all land areas	Very likely
Very likely	Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely
Very likely	Reduced diurnal temperature range over most land areas	Very likely
Likely, over many areas	Increase of heat index[a] over land areas	Very likely, over most areas
Likely, over many Northern Hemisphere mid-to high latitude land areas	More intense precipitation events[b]	Very likely, over many areas
Likely, in a few areas	Increased summer continental drying and associated risk of drought	Likely, 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, over some areas
Insufficient data for assessment	Increase in tropical cyclone mean and peak precipitation intensities	Likely, over some areas

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

[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.

mulation (*6*). The models couple known laws of physics with prescribed initial and boundary conditions of the atmosphere to compute the evolving state of the global atmosphere, ocean, land surface and sea ice in response to external natural and anthropogenic forcings. Boundary conditions are external factors that influence Earth's climate system, such as the intensity of sunlight, the composition of the atmosphere, etc. The climate system adjusts when one or more of these external factors change: for example, global average temperatures would be expected to increase with an increase in solar output. The ultimate aim is to model as much as possible of the climate system, especially the complex feedbacks among the various components.

A number of models are in operation in various research institutes and universities worldwide. Although the models are based on the same laws of physics, each has different ways of dealing with processes that cannot be represented explicitly by physical laws, such as formation of clouds and precipitation. Variations in these parameterizations lead to different regional projections of climate change, particularly for precipitation.

AOGCMs cannot simulate all aspects of climate and there are large uncertainties associated with clouds, yet there is increasing confidence that they can provide useful projections of future climate. This is due to their improved ability to simulate the important interactions between ocean and atmosphere for past and current climate on a range of temporal and spatial scales (*5*). In particular, simulations that include estimates of natural and anthropogenic forcing reproduce the large-scale changes in surface temperature over the twentieth century

(*5*). Current AOGCMs simulate well some of the key modes of climate variability such as the North Atlantic Oscillation and ENSO.

AOGCMs generally have horizontal spatial resolutions of about 250 km for their atmospheric component. This coarse spatial scale creates problems for successfully simulating possible regional climate change and its impacts. For example, two AOGCMs were used in the United States' National Assessment of the Potential Impacts of Climate Variability and Change. In one (from the UK Hadley Centre) the state of Florida was too small to be resolved, and in the other (the Canadian climate model), the Great Lakes were not represented. It is not possible to project regional climate patterns with confidence if significant geographical features are missing.

With limitations of spatial scale and other factors, AOGCMs still have difficulty portraying accurately precipitation patterns in mountainous regions and resolving important synoptic weather features (such as Mesoscale Convective Systems) that strongly influence precipitation patterns and amounts in many agricultural regions. The typical biases in reproduction of observed regional scale climate by AOGCMS are in the range of about ±4 °C for temperature, and −40 to +80% for precipitation (*29*). However, larger biases do occur. It is assumed that the ability to reproduce faithfully the current climate is a necessary condition for simulating future climate in a meaningful way (*30*).

Some techniques can ameliorate the problem of spatial scale. These regionalization techniques include statistical downscaling; regional climate modelling; and application of high resolution and variable resolution atmospheric models (AGCMS). All of these result in higher resolution simulations and, usually, better representation of regional climate (*31*). Statistical downscaling and regional modelling are the most popular techniques that have been used to provide improved regional climate representation for use in impacts studies (*30–35*). The guiding principle of both techniques is to use output from the coarse resolution AOGCMs to produce more detailed regional information.

In regional modelling, lateral and initial boundary conditions from an AOGCM are used to drive regional climate models (usually derived from mesoscale weather forecasting models) over a particular region of interest. AOGCMs provide the large-scale responses of the climate system while the regional model provides regional scale details. Regional models, which are run at higher resolutions (e.g. 30–50 km) are much more successful at simulating accurately regional climate, particularly in regions with complex topography, coastlines, or land use patterns. This ability to reproduce regional climate is limited, however, by the quality of the boundary conditions from the global model. Regional models cannot overcome large errors in the AOGCMs. Climate change experiments with regional models have been performed over many regions, including North America, Europe, Australia, China and India (*36*).

In statistical downscaling, the cross-scale relationship (i.e. large scale to regional/local scale) is expressed as a function between large-scale variables (predictors) and regional or local scale climate variables (predictands). Usually the large and local scale variables are different. It is important that the predictor variables be of relevance to the local variables. The technique of statistical downscaling relies on the assumption that the statistical relationships developed under observed climate conditions are valid under future climate conditions and that the predictors fully represent the climate change signal. The literature on statistical downscaling is quite large and the technique has been applied over most regions of the world (*30–31*).

These regionalization techniques sometimes produce climate changes, particularly of precipitation, that differ substantially from those of the global model that provides the large scale information for the techniques. There remains uncertainty regarding which projection of climate change (from the global model or from the regionalization technique) is more likely correct. However, at least in the case of regional modelling, there is good evidence to suggest that in regions of complex topography, the regional model is more apt to provide a more realistic response to increased greenhouse gases. Applications of regionalized scenarios to impacts models (e.g. hydrologic and agricultural models) usually produce impacts that are different from those obtained using the corresponding coarse scale scenario (*35*).

Despite the regional climate limitations of AOGCMs, they remain the major source of information on possible climatic changes that can be useful for projections of possible health impacts of climate change. However, scenarios developed using regionalization techniques will become increasingly available. It is also the case that the typical spatial resolution of AOGCMs will continue to improve in the coming years.

The rate of climate change also is of particular importance for understanding potential impacts, especially from the point of view of possible adaptations of human and natural systems. Some periods of past climate change occurred very rapidly. For example, during the last major ice age shifts of temperatures of up to 5 °C occurred in fewer than 50 years (*20*). Moreover, the recent rate of global temperature change in the last (20th) century is the greatest century scale change in the past millennium. The range of climate change indicated by the projected changes from climate models represents rates of change from roughly 0.14 to 0.58 °C per decade. It is expected that natural ecosystems in particular could have difficulty in adapting to the higher rates of change. There are also issues of very sudden changes as well as climate surprises (*37*). These include such events as the possible collapse of the West Antarctic Ice Sheet and the shutting down of the thermohaline circulation of the ocean in the North Atlantic. Such punctuated events would have dramatic effects on sea level rise for the former phenomenon and temperature for the latter. However, neither event is considered to have any significant likelihood in the next 100 years (*26*).

Exposure assessment

This section begins the discussion, continued throughout the remainder of the book, on how weather, climate variability and change can influence population health. There are descriptions of some of the methods and tools that can be used to assess exposure, along with illustrative examples. Further discussion of methods to assess relevant exposures to weather and climate can be found in Ebi and Patz (*1*).

Studying the natural complexities of weather and climate variability in relation to health outcomes offers unique challenges. Weather and climate can be considered over various spatial and temporal scales, with different scales of relevance to different health outcomes. For example, one categorization of temporal scales is into episodes, short-term weather variability and longer-term variation. The consequences of a single event, from a heatwave to an El Niño event, may be useful analogues for similar events. However, a single event may not be representative of all events; it might be weaker or stronger, or may be shorter or last longer than typical events.

Although informative for future directions in research and adaptation, the predictive value of analogue studies may be limited because future events may differ from historical events and because the extent of vulnerability of a population changes over time. The 1995 heatwave caused considerably more loss of life in midwestern states in the United States than a similar heatwave in 1999, in part because of programmes established in the interim (*38*). There are similar issues for geographical analogues, such as using the current experience of heatwaves in a more southern region to predict what might happen in the future in a more northern region. Regions differ on a number of important factors, including living standards and behaviours. Therefore, scenario-based modelling approaches are needed to project what might happen under different climate conditions.

As noted in other chapters, one of the difficulties faced by researchers studying the health impacts of climate variability and change is the often limited availability of both weather and health outcome data on the same temporal and geographical scale.

Exposure assessment begins by incorporating a definition of the exposure of interest into the study hypothesis. To use heatwaves as an example, a heatwave needs to be defined and methods for assessment determined. Heatwaves may be defined by temperature alone or a combination of temperature with other weather variables. There are various definitions of heatwaves. In the Netherlands, for example, the Royal Meteorological Institute defines a heatwave as a period of at least five days, each of which has a maximum temperature of at least 25 °C, including at least three days with a maximum temperature of at least 30 °C (*39*). It should be noted that the adverse health effects observed during and following a heatwave do not depend on weather alone: the physiological, behavioural and other adaptations of the population exposed to the heatwave are additional determinants of outcomes.

As well as defining the exposure of interest, decisions need to be made on the appropriate lag period between exposure and effect, and how long health outcomes may be increased after an exposure. Lag periods ranging from a few days to a year have been used, depending on the presumed underlying mechanism of effect. Deaths in the 1995 Chicago heatwave were highest two days after temperatures peaked (*40*). In a study of viral pneumonia, a seven-day lag was used (*41*); a study of water-borne disease outbreaks used lags of one and two months (*42*); and studies of El Niño and malaria epidemics used one-year (*43–45*).

The following examples describe a variety of approaches used to summarize exposures to weather and climate. Informative exposure assessment is required for development of quantitative estimates of current vulnerability to climate-sensitive diseases using empirical epidemiological approaches.

An example of an episode analysis is a study that took advantage of the 1997/8 El Niño extreme event to assess the effects of unseasonable conditions on diarrhoeal disease in Peru (*46*). Checkley et al. used harmonic regression (to account for seasonality) and autoregressive-moving average models to show an increased risk of these diseases following the El Niño event.

Synoptic climatological approaches are one method used to summarize short-term weather. For example, McGregor investigated the association between weather and winter ischaemic heart disease deaths (*47*). A principle component analysis followed by a cluster analysis of meteorological data for seven weather variables was used to determine winter air masses. Increases in ischaemic heart disease mortality appeared to be associated with concurrent meteorological conditions and with antecedent and rapidly changing conditions.

Time series analyses are used frequently to analyse exposures associated with short-term variability of climate. Time series analyses can take account of cyclical patterns, such as seasonal patterns, when evaluating longitudinal trends in disease rates in one geographically defined population. Seasonal patterns may be due to the seasonality of climate or to other factors, such as the school year. Two generally used approaches to time series analyses are generalized additive models (GAM) and generalized estimating equations (GEE). The generalized additive model entails the application of a series of semi-parametric Poisson models that use smoothing functions to capture long-term patterns and seasonal trends from data. The generalized estimating equation approach is similar to GAM in the use of a Poisson regression model to estimate health events in relation to weather data. However, no *a priori* smoothing is performed for the time series. Instead, the GEE model allows for the removal of long-term patterns in the data by adjusting for overdispersion and autocorrelation. Autocorrelation needs to be controlled for in time series data of weather measurements because today's weather is correlated with weather on the previous and subsequent days. Overdispersion may be present in count data (health outcomes) that are assumed to follow a Poisson distribution.

Time series analysis was used in a study that described and compared the associations between certain weather variables and hospitalizations for viral pneumonia, including influenza, during normal weather periods and El Niño events in three regions of California (*41*). Temperature variables, precipitation and sea surface temperature were analysed. Sea surface temperature was included as a marker for weather variables not included in the analysis, such as cloud cover. The cut points for the weather variables were approximately one standard deviation from the mean. A seven-day lag period was used. Specific changes in temperature or precipitation alone could not describe the hospitalization patterns found across the three regions. Also, developing a model based on either the inland or one of the coastal regions would not have been predictive for the other regions. These results underscore the difficulties in trying to model the potential health effects of climate variability.

Another example is a study of the association between extreme precipitation and water-borne disease outbreaks in the United States (*42*). The goal of the analysis was to determine whether outbreaks clustered around extreme precipitation events as opposed to geographical clustering. Curriero et al. defined extreme precipitation events with Z-score thresholds: scores greater than 0.84, 1.28 and 1.65 corresponded to total monthly precipitation in the highest 20%, 10% and 5%, respectively. A Monte Carlo version of Fisher's exact test was used to test for statistical significance of associations. The authors repeatedly generated sets of outbreaks in a random fashion, tabulating the percentage of these artificial outbreaks with extreme levels of precipitation at each step. This process produced a distribution of coincident percentages under the assumption of no association that was then compared with the observed percentage to calculate a p-value. Analyses were conducted at the watershed level, including outbreaks due to both ground and surface water contamination, and were further stratified by season and hydrologic region. Of the 548 outbreaks, 51% were preceded by a precipitation event above the 90%ile and 68% above the 80%ile ($p < 0.001$). Outbreaks due to surface water contamination were associated with extreme precipitation during the month of the outbreak, while outbreaks due to ground water contamination had the strongest association with extreme precipitation two months prior to the outbreak.

A study by Hay et al. demonstrates one approach for looking at longer-term variability (*48*). The authors used spectral analysis to investigate periodicity in both climate and epidemiological time series data of dengue haemorrhagic fever (DHF) in Bangkok, Thailand. DHF exhibits strong seasonality, with peak incidences in Bangkok occurring during the months of July, August and September. This seasonality has been attributed to temperature variations. Spectral analysis (or Fourier analysis) uses stationary sinusoidal functions to deconstruct time series into separate periodic components. A broad band of two to four year periodic components was identified as well as a large seasonal periodicity. One limitation of this method is that it is applicable only for stationary time series in which the periodic components do not change.

Another approach, used to study the association between El Niño events and malaria outbreaks, analysed historical malaria epidemics using an El Niño/Southern Oscillation index (*43–46*). This is discussed in more detail in chapter five.

Other statistical methods for analysing epidemiological studies of the health impacts of weather and climate are being developed. Improved methods still are needed to fit time series, as are methods to handle bivariate data (one series of counts and one of continuous data). However, these methods are not enough. Convergence of expertise, methods and databases from multiple disciplines is required to understand and prepare for a different future climate and its potential ecological, social and population health impacts. Capacity building to improve human and ecological data quality, and the development of innovative interdisciplinary methods, remain high priorities when facing the challenges of assessing actual and potential risks from global climate change.

Conclusions

Main findings

1. The IPCC Third Assessment Report concluded that the best agreement between climate observations and model simulations over the past 140 years was found when both natural factors and anthropogenic forcings were included in the models (*5*). Further, most of the warming observed over the past 50 years is attributable to human activities.
2. Human influences will continue to change atmospheric composition throughout the twenty-first century. Global average temperature is projected to rise by 1.4 to 5.8 °C over the period 1990–2100 (*5*). Global climate change will not likely be spatially uniform, and is expected to include changes in temperature and in the hydrologic cycle.
3. Studying the natural complexities of weather and climate variability in relation to health outcomes offers unique challenges. Weather and climate can be summarized over various spatial and temporal scales. The appropriate scale of analysis will depend on the study hypothesis. Each study hypothesis needs to define the exposure of interest and the lag period between exposure and effect.
4. The predictive value of analogue studies may be limited because future events may be different than historical events, and because the extent of vulnerability of a population changes over time. For these and other reasons, scenario-based modelling is needed to project what might happen under different climate conditions.

5. Analysis methods need to take account of the changing climate baseline. An additional consideration is that the shift in the mean of distributions of meteorological variables is likely to change the extremes of the distribution.

Research gaps

1. Innovative approaches to analysing weather/climate in the context of human health are needed. Many standard epidemiology approaches and methods are inadequate because these exposures operate on a population level. Methods used in other disciplines need to be modified and new methods developed to enhance the ability to study and project potential health impacts in a future that may have a markedly different climate.
2. Long-term data sets with weather and health outcome data on the same spatial and temporal scales are required. Currently it is not possible to answer key questions such as the contribution of climate variability and change to the spread of malaria in African highlands, because the appropriate health, weather and other data (i.e. land use change) are not being collected in the same locations on the same scales. There is currently little coordination across disciplines and institutions; these links need to be established and maintained.
3. Improved understanding is needed of how to incorporate outputs from multiple AOGCMs into health studies to highlight better the range of uncertainties associated with projected future health impacts. Including several climate scenarios can illustrate the range of possible future changes, thus allowing decision-makers to identify populations that may be particularly vulnerable to adverse health impacts and to use this information when prioritizing strategies, policies and measures to enhance the adaptive capacity of future generations.

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