3

Climate change so far

When people think of climate change, they usually think of the atmosphere first. They think of the kind of things they hear about in the weather forecast: air temperature, rainfall, winds. Professional climatologists usually have a more encompassing view of the climate system, which includes things like the oceans, the ice sheets and mountain glaciers. But let's go step by step and start with the atmosphere, and let's start by taking stock of what is actually happening there. Many people feel that significant changes are underway – that winters are not what they used to be in their childhood, or perhaps that summers never used to be so hot and dry in their region. While these are often valid observations, any single person's experience is necessarily rather limited to the region where they live and to what they can remember. So what do measurements from around the world show? That is what we will discuss in this chapter.

With each IPCC report, the picture is getting ever more clear. There is an obvious reason for this: since the first report in 1990, we have accumulated 17 more years of measurements. But in addition to that, a lot of work has been done on the quality control and a comprehensive analysis of errors in past measurement data sets, on filling gaps and on recovering data archives that had not yet been included, for example because they existed only on paper and not yet in digital format.

Temperature changes

As was explained in Chapter 2, the global mean surface temperature is ruled by a simple energy balance which involves the effect of greenhouse gases. It is therefore the best number to look at if one wants to see whether the increase in greenhouse gas concentrations is actually having the effect that is predicted by the physics of the greenhouse effect. The global mean temperature has the additional advantage that its natural variations are much smaller than the variations on a regional or local scale; this makes it easier to detect any long-term trend. The reason is simply that many natural climate variations cancel out when averaged over the globe. At any moment in time, some parts of the planet will be warmer than normal while others will be colder. As an example, the monthly temperature anomalies in Boulder, Colorado, have a range of 7 °C (meaning that in 90% of cases the average temperature of a particular June, say, is within a 7 °C wide interval). For the USA as a whole, this range of monthly anomalies is 3.9 °C, while for the globe it is only 0.8 °C. Annual anomalies are much smaller again than these monthly anomalies: if June was rather hot, there is still a chance that September or December (say) were colder than average, and such anomalies would partly cancel out.

The global mean surface temperature is computed by combining measurements of air temperatures over land and measurements of sea surface temperatures in the oceans. Air temperatures are measured at thousands of weather stations around the globe, while sea surface temperatures are measured from thousands of ships and buoys. These measurements are combined on a regular grid, so that every square kilometer of Earth's surface counts equally towards the global average, regardless of how densely the measurements are spaced.

The urban heat island effect

Errors in the computed global mean temperature arise mostly where the data coverage is thin – this is a problem in the tropics and the Southern

Hemisphere, especially around Antarctica, in the earlier times, particularly the nineteenth century but to a lesser extent still up to 1950. Another potential error source is the "urban heat island effect", which can affect weather stations in cities. For various reasons cities usually have a warmer microclimate than their surroundings; this can lead to a spurious warming trend at an urban weather station as the city grows. This warming is of course very real in the city concerned, but it is spurious in the sense that it is a highly localized effect not representative for a wider area. Most stations affected by the "urban heat island effect" are therefore excluded from the global records; they can be filtered out by comparison with nearby rural stations. Several studies have shown that the urban heat island effect causes only a tiny error in the computation of global temperature trends. For example, it was found that no differences exist in the warming trend computed for very windy days versus that for calm days. If the urban heat island effect did play a role, then clearly it should have a much larger impact on calm days. Also, studies for the USA and for China showed that the temperature trends computed using only rural stations were practically indistinguishable from those that included urban stations.

How global temperatures changed

After all these preliminaries about temperature measurements you may be curious what they actually show. This is seen in Figure 3.1. From the level in the second half of the nineteenth century, temperatures increased in two phases: first from the 1910s to the 1940s, and then more strongly from the 1970s to the present. Around 1950 (let's use the average 1946–1955), it was 0.2 °C warmer than at the beginning of the century (1896–1905). Global temperature remained near this level until the 1970s, after which it started a steady rise at a rate of 0.17 °C per decade until today. The decade 1996–2005 was 0.6 °C warmer than 1946–1955. The overall rise since 1900 is 0.7 °C when expressed as a linear trend, which understates somewhat the actual, non-linear increase. This warming trend is greater than any experienced since at least the Middle Ages (the eleventh century – see Chapter 6). Table 3.1 shows how the warming trend has accelerated over time, from 0.05 °C per decade for the past 150 years to 0.18 °C per decade over the past 25 years.

This time history is due to a combination of factors. First, there are *forced* temperature changes, that is changes driven by the kind of forcings discussed in Chapter 2 (see Figure 2.1). Superimposed on this are unforced, internal variations – you can think of them simply as random jitters. The latter mostly

Table 3.1. **Linear trend in global mean temperature over the past 25, 50, 100 and 150 years. Note that the trend is accelerating. The error bars reflect the fact that trends over shorter time periods can only be determined with less accuracy, due to the random variability also seen in Figure 3.1.**

	Period Years	Rate °C per decade
🟨	25	0.177 ± 0.052
🟧	50	0.128 ± 0.026
🟦	100	0.074 ± 0.018
🟥	150	0.045 ± 0.012

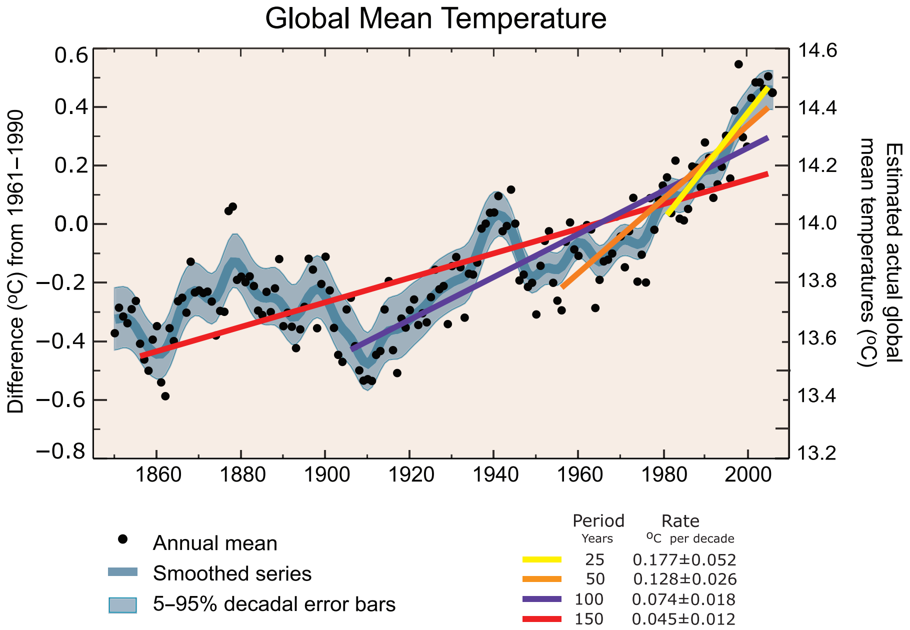


Figure 3.1 Global average surface temperature from 1850 to 2006. Dots show individual years, and the black line with its blue uncertainty range shows decadal averages. The temperature changes on the left scale are given with respect to the average over the years 1961–90.

cause the random variations from year to year. As the graph shows, these typically have an amplitude of about 0.1–0.2 °C. If one looks at just a short time interval – less than 10 years or so – such random jitters dominate temperatures, since the forced trend over such a short time is small. The table shows this: the error margin to which the trend can be determined gets ever larger when the time period gets shorter, and around 10 years or so the uncertainty is as big as the trend itself. It is thus pointless to look at such a short time period for answers on whether global warming has slowed or accelerated, as some recent newspaper articles have done.

Most of the longer-term variations are due to forced change, namely the human-caused changes in greenhouse gas concentrations and aerosol pollution, as well as the natural changes in solar activity and volcanic particles. For the first warming phase (1910s to 1940s), the dominant factors were probably the joint increase in both solar activity and greenhouse gas concentration. During the stagnant phase (1940s to 1970s), solar activity remained almost constant, while the warming due to increasing greenhouse gas concentrations was mostly cancelled by the cooling effect of increasing aerosol pollution. After that, sulfur filters on power station smoke stacks cleaned up this aerosol pollution in many parts of the world, so that from the 1970s the accelerating rise in greenhouse gas concentrations dominates the temperature record.

Record years

About record warm years, the IPCC report has the following to say:

> The warmest years in the instrumental record of global surface temperatures are 1998 and 2005, with 1998 ranking first in one estimate, but with 2005 slightly higher in the other two estimates. 2002 to 2004 are the 3rd, 4th and 5th warmest years in the series since 1850. Eleven of the last 12 years (1995 to 2006) – the exception being 1996 – rank among the 12 warmest years on record since 1850. Surface temperatures in 1998 were enhanced by the major 1997–1998 El Niño but no such strong anomaly was present in 2005. Temperatures in 2006 were similar to the average of the past 5 years.

At the time of writing, the latest data show that 2007 and 2008 also ranked amongst the top 10 warmest years on record. January and February 2008 turned out to be relatively cool (causing a flurry of misguided newspaper reports calling off global warming) due to exceptionally widespread snow cover in parts of Asia and cool ocean temperatures in the tropical Pacific (La Niña conditions, see Chapter 5). This brief cold snap was one of those “random jitters” mentioned above. It was gone again by March 2008, which ranked the second or third warmest March, depending on the data set used. Above the global land masses, it even was the warmest March since records began in the nineteenth century.

Land and sea temperatures

It is interesting to see where temperatures have increased most: over land or sea, in the north or south? The partitioning in land and ocean is shown in Figure 3.2. Since the 1970s, temperatures over land have increased much faster than over the oceans. This is to be expected for several reasons. The oceans are wet, so a large part of the incoming energy goes into evaporation rather than heating. On land, evaporation is limited by the available moisture – when the soil is dry, heating is greater. The oceans also act as a big heat buffer: they store heat and therefore respond with a delay. That's a boon and a curse. It reduces the warming we have experienced so far, so that's good. But it also could lull us into complacency by hiding some of the warming we are committed to from the greenhouse gases we've put already into the atmosphere. Since we live on land, it is important to realize that land areas are and will be warming more rapidly than the global average numbers most often cited.

If we compare the northern and southern halves of our planet, we find that the temperature rise has been more steady since the 1950s in the Southern Hemisphere. The stagnant phase until the 1970s was mostly a northern phenomenon – this is consistent with the idea that it is due to aerosol cooling, as most of the smog pollution happened in the north. Overall, the Southern Hemisphere has warmed slightly less than the Northern Hemisphere – that

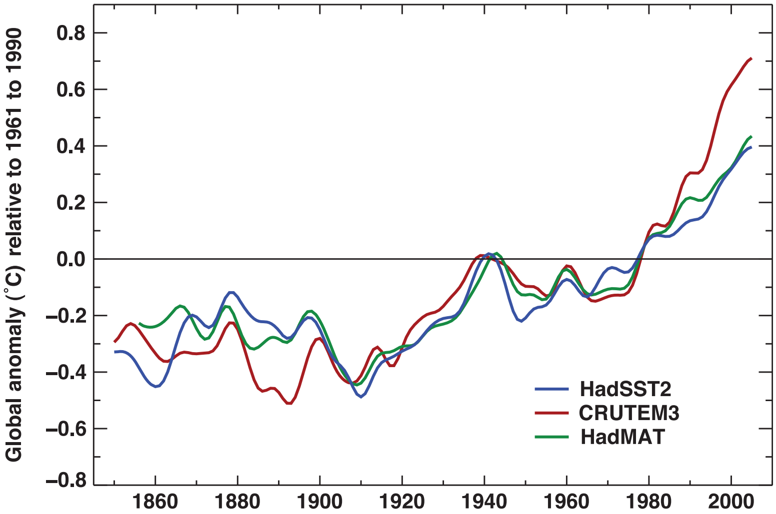


Figure 3.2 Warming over land and sea: the blue curve shows global sea surface temperatures, the green curve the air temperatures over the oceans, and the red curve the air temperatures over land.

is likely due to the fact that most of the land areas, which warm faster, are in the north, while the Southern Hemisphere is mostly ocean.

The map of warming

A map of the warming trend since 1900 is shown in Figure 3.3. We see that warming is evident almost everywhere on the planet, with the largest warming over the northern continents, where in a few places it already exceeds 2 °C. Thus, the overall warming trend is already so strong that it has overwhelmed most of the internal regional climate fluctuations, which would be equally likely to be warming or cooling during any given time period.

The most prominent patch that shows cooling is an area of the northern Atlantic south-east of Greenland – exactly the same spot where models show a minimum of warming, some even a cooling, in simulations forced by greenhouse gases (see Figure 7.1). The IPCC report does not discuss this further, but in our view the cooling in this area is likely a systematic response to greenhouse gases, rather than this being an area where natural variability has happened to cause some cooling that bucks the global warming trend. In the models, a cooling or reduced warming in this particular area is usually a response to a slowdown in the Atlantic ocean circulation. This cooling patch may thus be an indication that this circulation has slowed down during the past century – whether it has or not is an area of intense scientific debate (see Chapter 5), as conclusive data are missing and further analysis of this issue is required. The report concludes on this question that we simply don't know, as yet.

Over the past 50 years, the night-time temperatures have increased more than daytime temperatures. That is, the daily minimum has increased by 1.0 °C, the maximum only by 0.7 °C. This could be due to aerosol and cloud cover changes (smog and clouds tend to make the day cooler but the night warmer; on clear nights more heat escapes into space).

Surface, troposphere and stratosphere

We've so far talked about surface measurements taken at weather stations near the ground. But temperatures are also measured higher up in the troposphere (the lowest 10–15 km of the atmosphere), by weather balloons and satellites. For years and until quite recently, "climate skeptics" claimed on their websites that there is no global warming, as the satellites don't show any. This claim was wrong, but it was based on a real discrepancy between the surface measurements and those from satellites. Satellites cannot tell what the surface temperature is, but they measure the temperature of the bulk of the

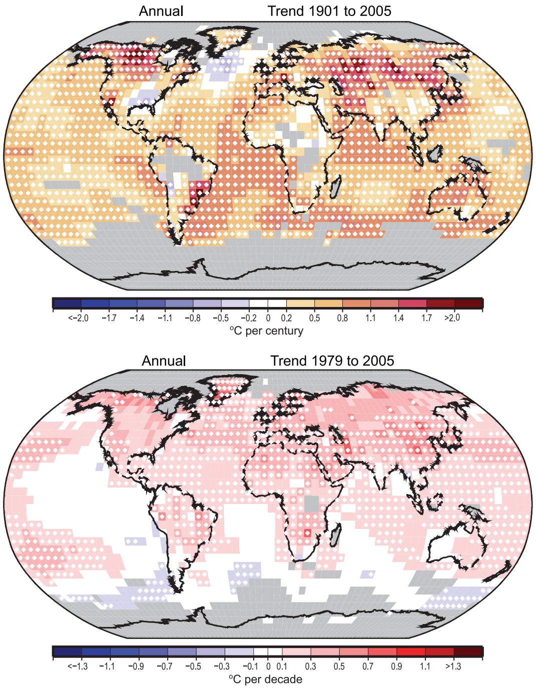


Figure 3.3 Map of the temperature change over the twentieth century. Shown is the linear trend of temperatures taken from 1902 to 2005. Gray regions lack sufficient data to determine the trend. In boxes marked by a white "+", the trend is statistically significant.

troposphere by measuring radiation from the troposphere that arrives at the satellite. This initially indicated considerably less warming than the surface records, a somewhat puzzling result. This discrepancy has now finally been resolved: it was mainly due to errors in the satellite analysis (which involves a number of complex corrections for changes in the orbit and instrument calibration issues). After several errors were discovered and fixed, surface measurements, balloons, and satellites now give a consistent picture of our warming Earth, with the troposphere warming slightly more and a lot more uniformly than the surface climate, as predicted by models (see Figure 3.4).

The stratosphere (the layer above the troposphere), on the other hand, *is* cooling. Balloon and satellite data show 1.5 °C cooling since 1950. This is expected for two reasons. The first is the increase in greenhouse gases, which traps heat in lower layers of the atmosphere, while it helps to radiate heat away from the stratosphere

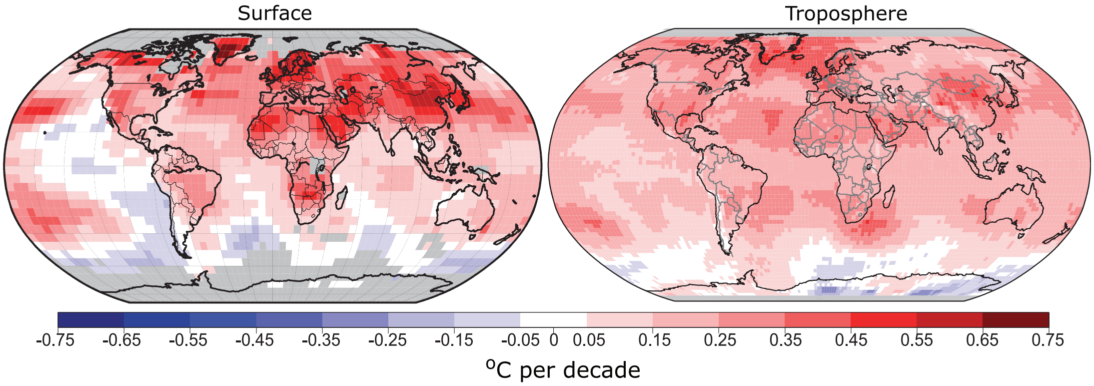


Figure 3.4 Map of temperature changes (linear trends) from 1979 to 2005. Left shows surface data, right shows data for the troposphere as measured from satellites.

(this difference in the vertical is one way to tell apart the effect of greenhouse gases and the effect of solar activity variations). The second is the ozone loss in the stratosphere. Ozone is a major absorber of solar UV radiation and therefore a major heat source in the stratosphere.

Rain and snow

Climate is not just temperature. For land ecosystems and agriculture, precipitation (rain, hail, snow) is at least as important. So how has precipitation changed? This is far more difficult to measure than temperature, not just because precipitation measurements are less precise in themselves, but also because precipitation is a lot more variable in time and space. We start with a little physics to understand some of the key features of precipitation.

A little physics

Precipitation arises when moisture condenses in the atmosphere, usually as the air rises. Air cools as it rises since the pressure drops as you go up. Since colder air can contain less water, the water falls out on the way. Air rises when it has to cross mountains, or when it slides over colder air (in a warm front), or when cold heavy air pushes underneath it (in a cold front), or when it is heated from below. The spotty nature of precipitation and the many physical processes that play a role make for complex patterns of change, quite different from those for temperature.

Nevertheless, two simple physical principles give us some guidance as to what we may expect. The first is that *evaporation increases* in a warmer climate (as long as there is water available, as is always the case over the oceans). What goes up must come down. Hence precipitation, on average, also must increase in a warmer world. Moisture on average only stays about five days in the atmosphere until it rains out again.

The second, not directly related principle is that *warmer air can contain more moisture*. An established law of nineteenth-century physics, the Clausius–Clapeyron relation, states that the amount of water vapor that fits into a given volume increases by 7% for each °C warming: that's how much water vapor you can evaporate into a parcel of air until it can take no more. This law will tend to increase extreme rainfall events, which typically arise when moisture-loaded air is forced up (say, over a mountain range) and is thereby "squeezed out like a sponge," as happened during the Elbe River flooding disaster in Europe in 2002. In a warming climate, the sponge is getting ever larger according to the Clausius–Clapeyron relation.

The "relative humidity" measure familiar to all of us simply states how close to saturation an air parcel is. A humidity of 90% means that the air contains 90% of the maximum moisture that it can hold – add 10% more and it will be saturated. The average relative humidity in the atmosphere remains almost constant during climate change. Even if evaporation increases, the extra water just rains out of the atmosphere when on average a certain percentage of the saturation level is reached, and this is what ultimately determines how much water is in the atmosphere. Because of this, as the water-holding capacity goes up, the *average* water vapor content also goes up – not just the water content of saturated air parcels discussed in the previous paragraph. The data support this; they show that, over the oceans, vapor content in the atmosphere has increased in line with the Clausius–Clapeyron relation. It is estimated that water vapor content has increased by about 5% in the atmosphere over the oceans during the past hundred years. Over land the increase is found to be a bit smaller. Again that's expected, as moisture supply is limited over land. Since water vapor is a greenhouse gas, the increase in water vapor content (caused by the warming) in turn enhances the warming. This is one of the amplifying feedbacks that make the climate system so sensitive to perturbations.

A final and very simple physical consideration: as temperatures rise, we may expect that a larger fraction of precipitation falls in the form of rain, rather than snow, which has implications for example for water storage in the snow pack and for glaciers.

Observed rainfall changes

A global map of measured precipitation changes over the past century is shown in Figure 3.5. We warned you it would be rather patchy – and it is. Unlike temperature, which has increased almost everywhere on the planet (see Figure 3.3 – "global warming" is thus an appropriate term), precipitation increases in some parts of the world and decreases in others. The gray areas (or blue over the ocean) are regions where the data coverage does not suffice to compute reliable trends, while white regions have enough data, but no trend. The remaining, colored parts of the map show that in some large regions precipitation has indeed increased, for example in the eastern parts of North and South America, in the northern parts of Europe and in central and northern Asia. In other regions, rainfall has significantly decreased: in the Mediterranean region, in the Sahel, in southern Africa and in some parts

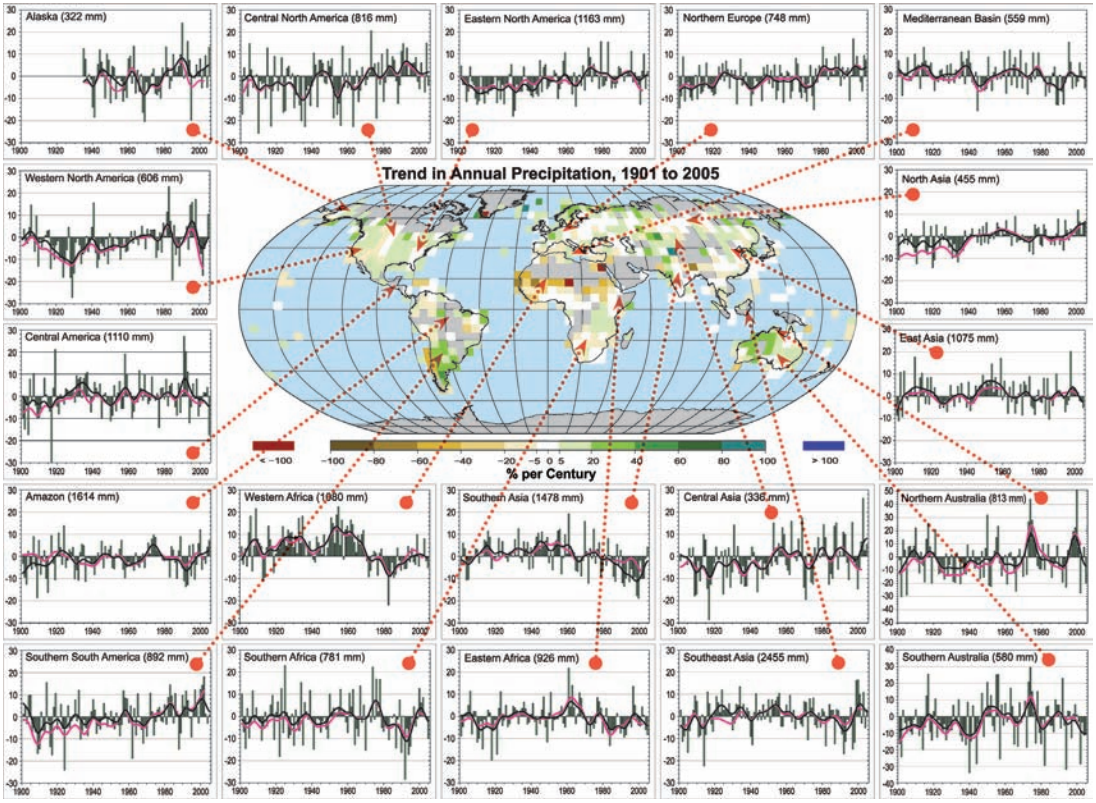


Figure 3.5 Precipitation changes around the world. The map shows the linear trends from 1900 to 2005 over land (gray areas lack sufficient data), and the time series show individual regions. Precipitation is given as a percentage of the mean, where the mean is given at the top of the panels for the period 1961–90. In contrast to temperature trends, precipitation trends are far more "patchy" and can point in either direction: up in some regions, down in others.

of southern Asia. Behind many of these 100-year trends lies a more complex time evolution with ups and downs, which are not yet fully understood.

People, and particularly farmers of course, care not only about the average amount of rain or snow that falls each year. They also care about seasonality, namely about how much rain falls in winter, summer or spring. In some parts of the world, rainfall has gone down in summer but is on the rise in winter, causing little change in the annual total – but increased flood risk in winter and drought problems in summer. In other regions, where precipitation mostly falls in winter, a larger fraction is now falling as rain. This reduces the snow pack in the mountains, which is an important source of runoff in summer when water is most needed, as well as the basis of much winter tourism.

Figure 3.6 The "flood of the century" in June 1999 of Lake Constance, central Europe's third largest lake, situated between Germany, Switzerland, and Austria.

And people care about the extremes: about the number of heavy rainfall events that cause flooding, or about long stretches without rain that can cause drought and water shortages. One important observation is that heavy rainfall events are on the rise: in many parts of the world, the fraction of the total annual rainfall that comes down on just a few very wet days has increased (Figure 3.6). A likely explanation is the physical effect mentioned above, namely that warmer air can hold more water, so more can come down during extremely wet days. This is found to be happening even in regions where the overall rainfall has not increased.

The flip side of flooding is drought. Drought can be defined in various ways, since the amount of rainfall is just one part of the issue. The amount of water that is evaporated and the amount stored in the soil are equally important. The most commonly used measure for drought is the Palmer Drought Severity Index (PDSI), which combines monthly precipitation totals and temperatures. This accounts for the fact that in warmer temperatures more rainfall is required to maintain soil moisture and healthy vegetation. The data to compute the PDSI are readily available, and a map of changes in this index is shown in Figure 3.7. These data show that drought severity has increased over the past hundred years in many parts of the world, for example in the larger Mediterranean region, the Sahel, southern Africa, the Amazon region, India and parts of China, the Caribbean and the eastern half of

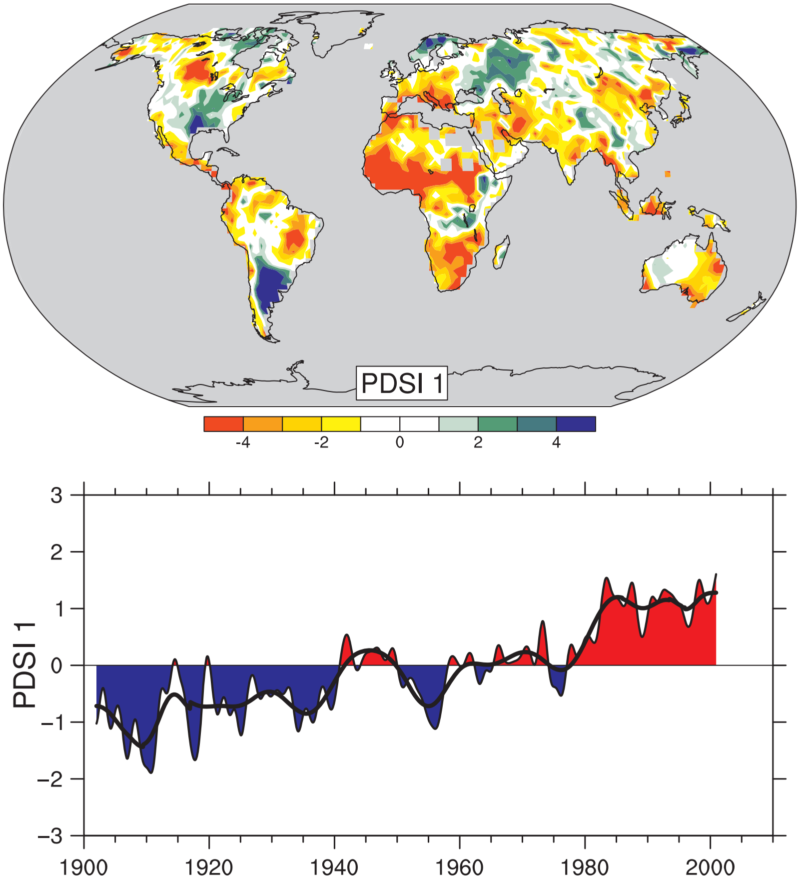


Figure 3.7 Change in drought severity as measured by the Palmer Drought Severity Index. The map shows a global map of the main pattern of change, while the lower panel shows the corresponding time evolution. Drought severity has increased in many parts of the world, including most of Africa, the Mediterranean region, Central America, and the eastern half of Australia (see also Chapter 8).

Australia. Only a smaller part of the planet has seen a reduction in the drought risk, despite the fact that global rainfall has increased. Based on this drought index, very dry areas (defined as land areas with a PDSI of less than –3.0) have more than doubled in extent since the 1970s. As we will see in Chapter 7 on future changes, the already worsening drought situation is expected to get a lot worse.

Clouds and radiation

As we saw in Chapter 2, the way humans affect the climate system is not by producing heat, but by interfering with radiation – either with the

Figure 3.8 Fur women busy drawing water for their animals and families at one of the few wells in Darfur in 2005. Increasing drought problems in the Sahel have contributed to the violent conflict in Darfur.

incoming solar radiation, or with the outgoing longwave radiation. Hence it is important to monitor changes in the radiation budget directly. Clouds have a big impact on both types of radiation, as everyone knows from personal experience. When clouds hide the sun during the day, it gets a lot colder, while a blanket of clouds at night keeps the longwave radiation in and makes for a mild night. This (and the fact they are difficult to model) makes cloud cover changes the prime reason for the uncertainty we still have about how sensitively the climate system will respond to human interference (see the discussion of climate sensitivity in Chapter 7).

Clouds can be monitored either from the Earth's surface or from satellite, but only with some difficulties. If there are several layers of cloud, observers at the surface tend to see only the lower, while satellites only see the upper layer. Observations from the surface go far back in time, but are available only

Figure 3.9 Image of the sky taken at the Arctic Facility for Atmospheric Remote Sensing, a permanent cloud monitoring station in Alaska.

from a limited number of stations, while satellite observations have a global coverage and frequent sampling, but they start only in the 1970s and are affected by biases that arise from the frequent changes of satellite and other problems.

Surface observations suggest that, since 1950, cloudiness has increased in many large continental regions, including the USA, the former USSR and Western Europe. This is consistent with an increase in precipitation and a decrease in the difference between day- and night-time temperatures. However, trends since the 1970s are small and less coherent, and not fully consistent between surface and satellite observations. Hence, the IPCC report comes to the scientifically rather unsatisfying conclusion: "at present there is no clear consensus on changes in total cloudiness over decadal time scales."

Radiation at the top of the atmosphere can be monitored from satellites (most notably, the Earth Radiation Budget Satellite, ERBS). This provides global cover but poor time sampling. The satellite data show some changes between the 1980s and 1990s, but measurements are not fully consistent between different systems and the time period is too short to establish meaningful trends.

In addition there is a limited number of high-quality ground-based stations, which provide excellent time coverage. The Swiss radiation monitoring network showed an increase in longwave radiation reaching the surface over the past 20 years related to an enhanced greenhouse effect, but the conclusions that can be drawn from one small region are naturally very limited since the local near-surface energy balance is complex and includes many contributing factors.

Surface measurements of radiation from land stations showed a widespread decrease of solar radiation by about 7 W/m^2 between 1970 and 1990, which has been dubbed "global dimming." This trend has turned out to be mostly in urban areas, not global, and probably caused by aerosol pollution – in other words, by smog and associated changes in cloud cover. Since then, this trend has reversed, and surface radiation has recovered by about 6 W/m^2.

Overall, the measurements of clouds and radiation from satellites still have some teething problems to sort out and need to continue for longer to provide robust trends, while ground-based observations are too localized to draw firm conclusions about global changes. At this stage, these measurements thus neither provide proof nor a reason to question the idea that the anthropogenic rise in greenhouse gases is responsible for the observed global warming.

Patterns of atmospheric circulation

Winds in the atmosphere are organized in a few distinct large-scale patterns, such as the trade winds, the "westerlies," the monsoons, and the jet streams. These are called atmospheric circulation patterns. They include large overturning cells such as the Hadley cells and Walker cells in the tropics and subtropics. In addition, there are particular patterns of circulation variability: patterns of irregular, large-scale oscillations such as the El Niño/Southern Oscillation (ENSO) phenomenon. The IPCC report finds that these circulation and variability patterns of our atmosphere are changing to some extent.

On the westerly winds that dominate the mid-latitude air flow, the report concludes that they have generally increased in both hemispheres over the past 50 years. The storm tracks – the main routes that low pressure systems follow in mid-latitudes – have moved polewards, meaning for example that in Europe, Scandinavia is now getting more westerly storms while Spain is getting

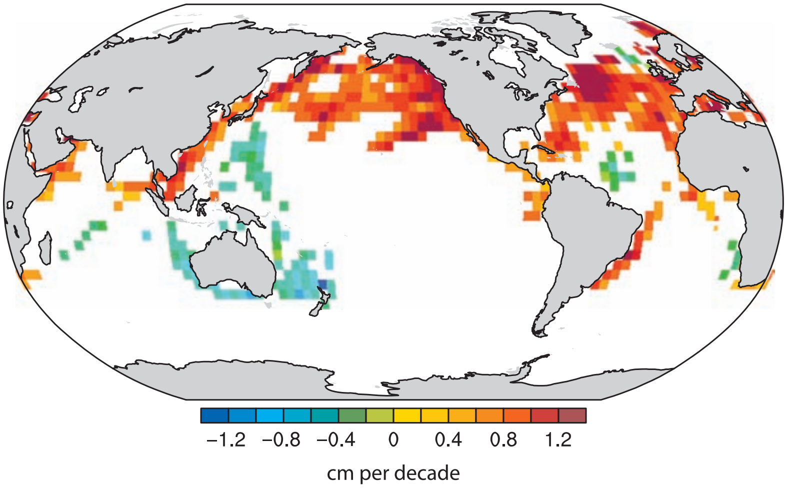


Figure 3.10 Trends in wave heights in the ocean from 1950 to 2002. White regions denote lack of data to determine trends; good data are available mainly near major shipping routes. In the northern Atlantic and Pacific, waves have become significantly higher.

fewer. The intensity of storms has increased, but the total number of storms appears to have decreased. There are, however, still significant uncertainties in these wind data, and not all studies reach consistent conclusions. The apparent increase in westerly winds is, however, supported by a trend towards increased wave heights observed in the northern Atlantic and Pacific (Figure 3.10).

On time scales of a few years, the dominant variability pattern of the atmosphere is the irregular oscillation between El Niño conditions (characterized mainly by exceptionally warm conditions in the eastern tropical Pacific) and the opposite extreme, called La Niña. This is a natural ocean–atmosphere oscillation that appears to have gone on for centuries, probably even for many millennia (with some interruptions). Although centered on the tropical Pacific, it has repercussions around the world. For example, El Niño conditions tend to cause flooding in Peru and California (Figure 3.11) but drought in Indonesia, Australia, the Amazon, and parts of Africa. There are different ways to measure the ups and downs of this oscillation. One common measure is the air pressure in Darwin (north Australia), which goes down during El Niño conditions and up during La Niña (see Figure 3.12). The record since 1865 shows that since the late 1970s, a tendency towards stronger and longer El Niño events is evident. Whether and how this is physically linked to global warming is not yet clear.

El Niño events tend to cause a warm anomaly in the global mean temperature, since a large amount of heat is released during these events

Figure 3.11 Flooded area in Lakeport, California, as a result of the 1998 El Niño event.

from the tropical Pacific Ocean into the atmosphere. The strongest El Niño event on record, in terms of the warmest sea surface temperatures reached in the eastern tropical Pacific, was that of 1997/8. This is probably the reason why 1998 was globally the warmest year on record (at least until 2005, which rivaled 1998 even without the help of an El Niño event, see Figure 3.1).

The report further discusses changes in a number of other patterns of circulation, such as the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), the Southern Annular Mode (SAM), and others. These all show interesting variations that are too complex to summarize here in a few sentences. Current research efforts are making good progress towards a better understanding of these patterns, which will in future allow us to better predict regional climate variations and their link to global changes. These efforts are spurred on by the successes in El Niño prediction, which are already saving society billions of dollars in avoided damages to agriculture.

A particularly important pattern of winds and seasonal rainfall is the monsoon, upon which the food production for a large fraction of the world's population depends, especially in southern and eastern Asia. Monsoon winds and rainfall are driven by seasonal temperature differences between land and sea: in summer the land is usually warmer than the ocean, in winter it

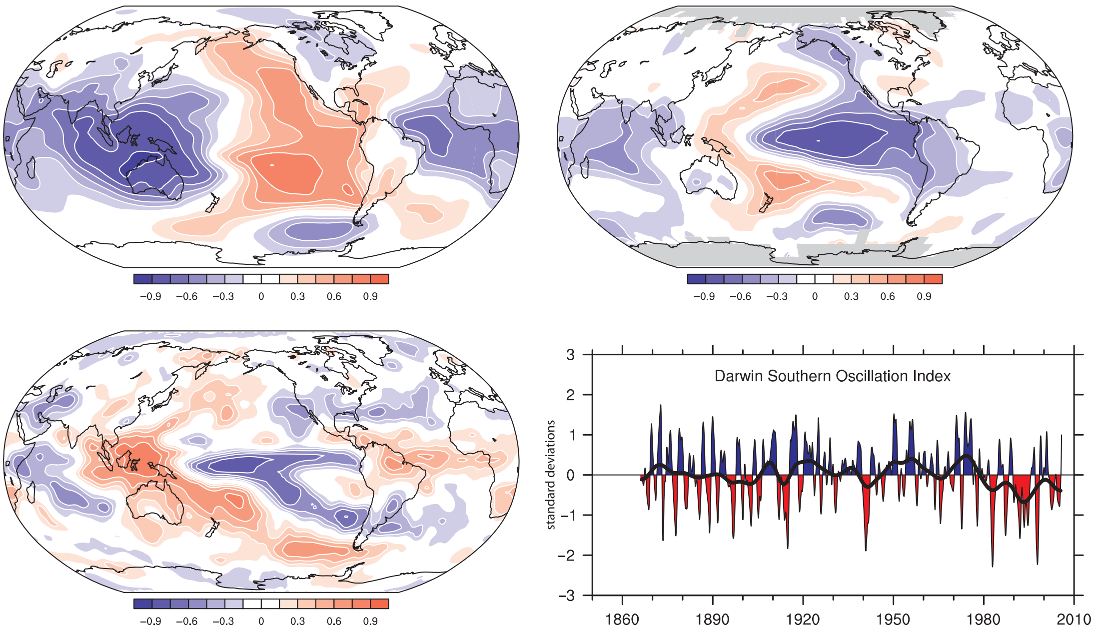


Figure 3.12 The three maps show the effects of the Southern Oscillation around the world. Top left shows the sea level pressure, top right the surface temperature and bottom left precipitation. An index of the Southern Oscillation is shown at bottom right, where the negative excursions of this index show El Niño events (e.g., in 1982/83, 1998). The maps measure the correlation with this index at each point on Earth; e.g., the map shows that a positive SOI (La Niña conditions) correlates with cold conditions in the western tropical Pacific and high rainfall over Indonesia. The reverse applies to El Niño conditions.

is the opposite. Changes in monsoon rainfall observed between two periods before and after 1975 (when a shift in atmospheric circulation was observed) are depicted in Figure 3.14. The African and south Asian monsoons have decreased, while the seasonal rainfall has increased in parts of South America and Australia. Studies show that the monsoon is influenced by a number of factors, particularly regional changes in sea surface temperatures (as occur, for example, with the El Niño phenomenon discussed above) and air pollution. This smog (e.g. the “Asian haze”) shades the incoming solar radiation that drives the monsoon by heating the land masses in summer, and it has therefore been linked to monsoon weakening.

Tropical storms

Tropical cyclones are highly structured, rotating storm systems that occur in the tropical region, but not right on the equator since the influence of the

Figure 3.13 Agricultural production in Asia is strongly dependent on regular, predictable monsoon rains. The image shows children celebrating the arrival of the monsoon in a street of Chittagong, Bangladesh.

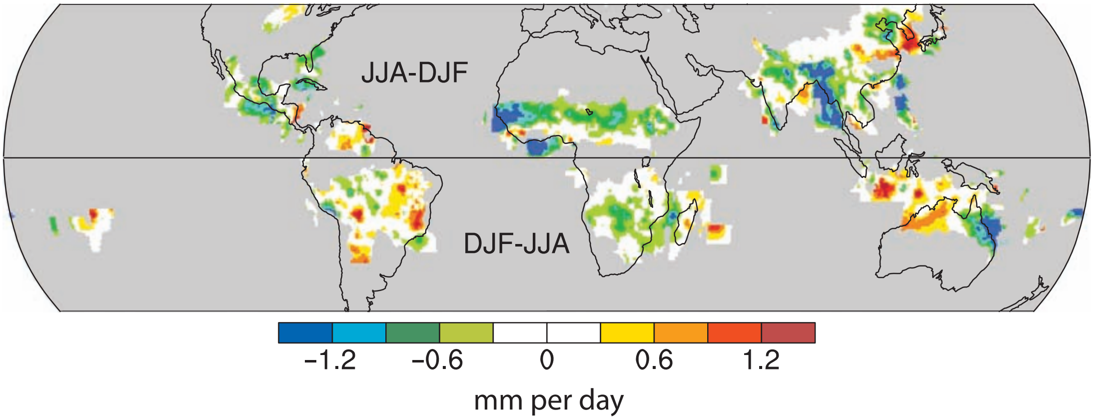


Figure 3.14 This map shows how the annual range in precipitation has changed since the middle of the twentieth century. This range is the difference between summer and winter rainfall, which in these latitudes is indicative of the monsoon. In the blue/green regions the monsoon has weakened.

Figure 3.15 Haze over mountains in Japan.

Earth's rotation on the winds vanishes there. Above a certain wind speed they have traditionally been called hurricanes in the Atlantic and eastern Pacific, and typhoons in the western Pacific. These storms are fueled by sapping energy from the warm ocean waters below – this is why they occur only in the tropics in the warm season over waters exceeding about 26 °C, and why they quickly die over land. In fact, tropical cyclones are a kind of valve through which the heat of the tropical summer sun is vented from the oceans.

Figure 3.16 People sheltering in Burma in the aftermath of typhoon Nargis, which caused over 100,000 casualties and made over one million people homeless. Nargis was a category 4 tropical cyclone. The number of strong cyclones (categories 4 and 5) has increased over the past 30 years in the Indian Ocean.

Public interest in tropical storms has increased strongly as a consequence of the extreme Atlantic season 2005 and the devastation of New Orleans by hurricane Katrina in August of that year. One or two extreme seasons of course cannot tell us much about long-term trends or about the important question of whether these trends are influenced by global warming. Neither can the fact that severe hurricanes also occurred over a century ago, before global warming. To establish whether any long-term changes in tropical storm activity are occurring, we need to analyze comprehensive data sets about these storms. This has been done in a number of studies by different research groups, which are reviewed and summarized in the IPCC report.

In short, the report finds trends since the 1970s towards more intense and longer-lasting tropical cyclones, but no trend in the total number that occur each year. It states:

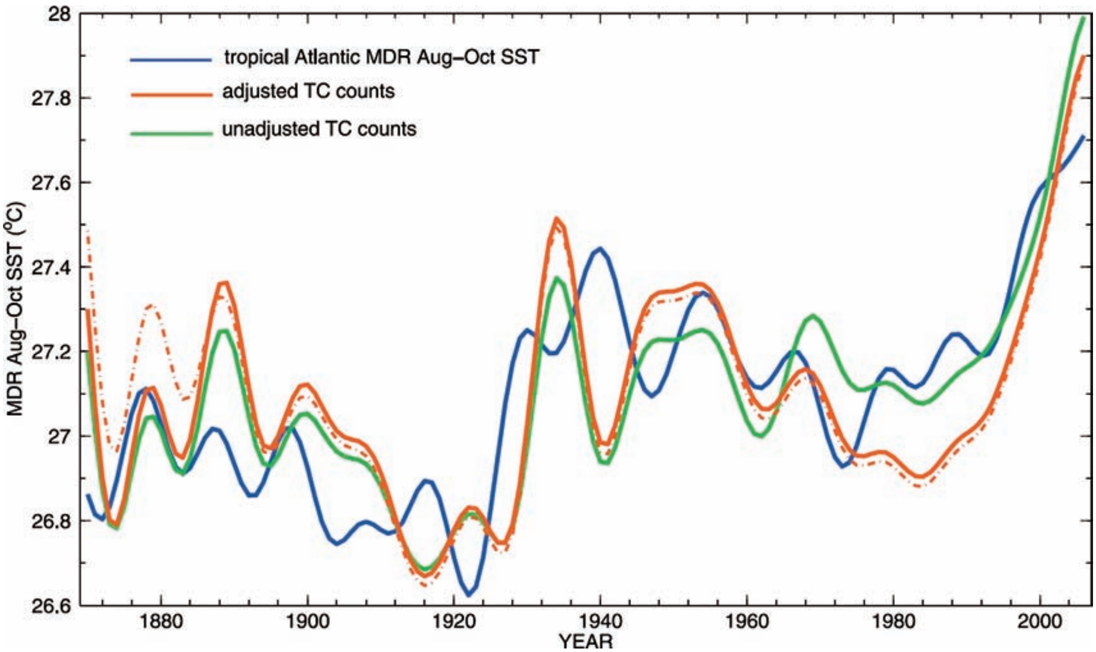


Figure 3.17 The figure shows the close link between sea surface temperatures in the main hurricane development region of the Atlantic (blue curve), and counts of North Atlantic tropical cyclones. The green curve shows the unadjusted cyclone numbers, while the orange curves show adjustments to account for possible missed cyclones in the past. All curves are smoothed over a decade.

Globally, estimates of the potential destructiveness of hurricanes show a substantial upward trend since the mid-1970s, with a trend towards longer storm duration and greater storm intensity, and the activity is strongly correlated with tropical sea surface temperature. These relationships have been reinforced by findings of a large increase in numbers and proportion of strong hurricanes globally since 1970 even as total numbers of cyclones and cyclone days decreased slightly in most basins. Specifically, the number of category 4 and 5 hurricanes increased by about 75% since 1970. The largest increases were in the North Pacific, Indian and Southwest Pacific Oceans. However, numbers of hurricanes in the North Atlantic have also been above normal in 9 of the last 11 years, culminating in the record-breaking 2005 season.

Given that warm ocean water is their energy source, it is physically plausible that a strong link between hurricane intensity and tropical sea surface temperatures (Figure 3.17) is observed, especially in the longer term. The rise in North Atlantic hurricane activity over the past 25 years occurred while tropical sea surface temperatures there rose to a record high – to a large part associated with global warming. This is why many hurricane experts are concerned about stronger hurricanes in the future, when sea surface temperatures will get even warmer.

Short-term variations in hurricane activity from year to year are large and depend strongly on a number of other factors, like the wind shear and the vertical stability of the atmosphere. For example, hurricane activity tends to be weaker in the Atlantic but stronger in the western North Pacific during El Niño events. Centers of greatest activity are shifting around, and a particularly active season in one area is often associated with a below-average season elsewhere, so that trends apparent in individual ocean basins partly cancel out in the global average. Large decadal variations and data problems in the pre-satellite era (before the 1970s) make long-term trends harder to detect.

Several studies since the IPCC report have found more evidence for an increase in hurricane activity over the past decades. A study by Carlos Hoyos and colleagues from the Georgia Institute of Technology in Atlanta found a strong global increase in the number of hurricanes of the strongest categories 4 and 5, and they identified rising sea surface temperatures as the leading cause (Hoyos *et al.* 2006). Meanwhile, scientific debate about data quality has continued, especially on the question of how many tropical cyclones may have gone undetected before satellites provided a global coverage of observations. Michael Mann and several colleagues concluded that such an undercount bias would not be large enough to question the recent rise in hurricane activity and its close connection to sea surface warming (Figure 3.17).

Causes of the observed climate changes

How can we establish the causes for these observed climate changes? This is known as the “attribution problem” in the jargon of climate science, and a great deal of effort has gone into studying this issue over the years. The IPCC *First Assessment Report* (FAR) contained little observational evidence of a detectable human influence on climate. Six years later, the IPCC *Second Assessment Report* (SAR) concluded that the balance of evidence suggested a discernible human influence on the climate of the twentith century. The *Third Report* concluded: “most of the observed warming over the last 50 years is *likely* to have been due to the increase in greenhouse gas concentrations.” Now, the *Fourth Report* says that the latter is *very likely*.

What are these conclusions based on? We need to distinguish two different kinds of reasoning here. First, there are so-called “detection and attribution” studies. This refers to a specific set of statistical techniques which allow us to "detect" climate changes in an observational data set (that means, to distinguish a real change from mere random fluctuations) and to "attribute" these changes to a set of causes. We will discuss this type of studies further below.

Second, there is the overall "balance of evidence." That simply includes everything we know about the climate system: our understanding of the physics (e.g. of the global energy balance that rules the changes in global mean temperature), all the information about past climate variations in Earth's history, all the data sets of recent weather and climate, and so on. Ultimately, it is of course this "balance of evidence" that determines the confidence we have in our understanding of the causes of climate change. This balance of evidence includes the results of the formal "detection and attribution" studies; they are one important piece of the puzzle but not the only one.

We can thus usually be more confident about the causes of certain climate changes than the results of "attribution" studies alone suggest. This important distinction is sometimes forgotten, even in discussions amongst climatologists. For example, scientists may find it very likely that the increase in extreme precipitation events (see above) is due to human activities, since we know that global warming is mostly due to human activities and there is a robust physical reason why a warmer climate would cause more extreme precipitation (the Clausius–Clapeyron relation mentioned earlier). Nevertheless, a formal "attribution" study may *not* find that extreme precipitation can be attributed to human effects in a statistical sense, simply because observational data are too patchy to prove a statistically significant link.

A simple analogue would be a kettle of water on a gas stove. If we light the gas and the water gets hotter, how do we know this is due to the gas flame? A formal "detection and attribution" study would require detailed temperature measurements to prove that the warming is not within the range of natural variations that could occur even without the gas flame, and that the heat spreads from below and not from above (where the sun shines through the window onto our kettle). Even in the absence of such measurements, we obviously would be quite sure that the warming is due to the gas flame, based on past experience and on understanding of the physics. We know from the past that the sun is too weak to heat the kettle so much, that the gas flame does this every time, and a physicist could easily calculate how fast the water should heat up given the amount of gas that is burned. Back to the climate system, "past experience" is the information from paleoclimate, the physics of the greenhouse effect has been well understood since the nineteenth century, and the observed rate of warming fits what is expected from a simple energy balance calculation.

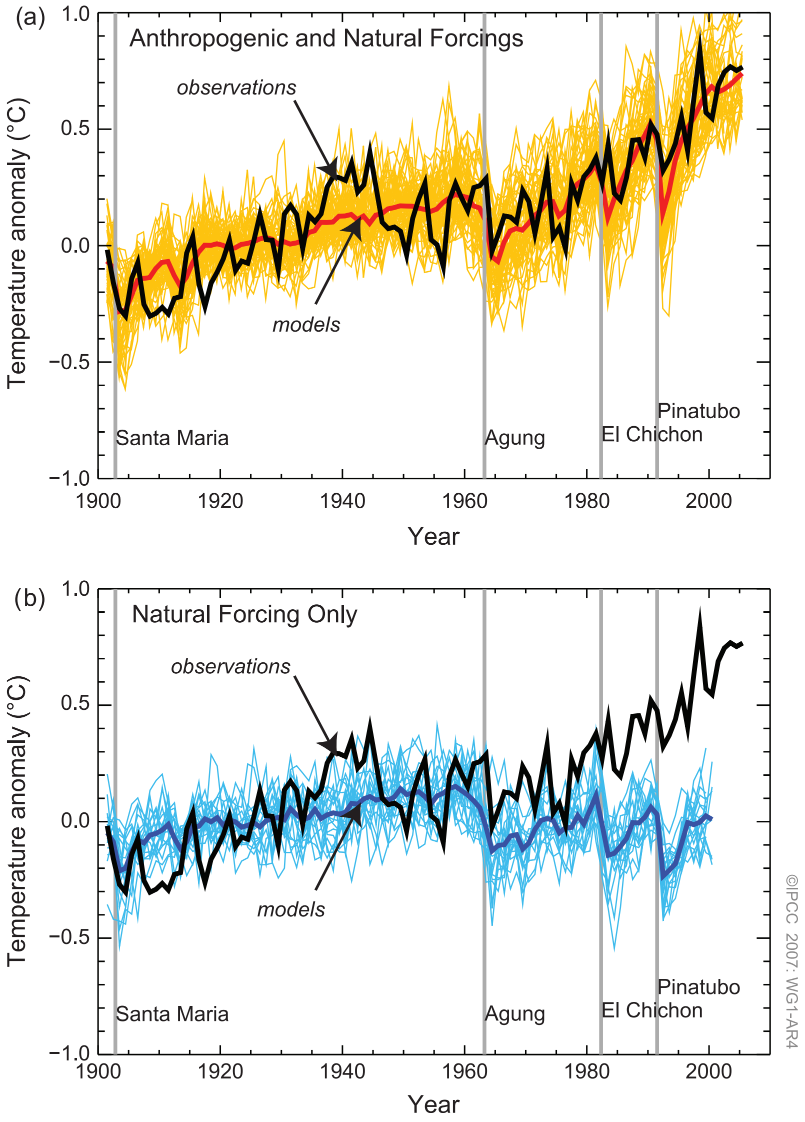
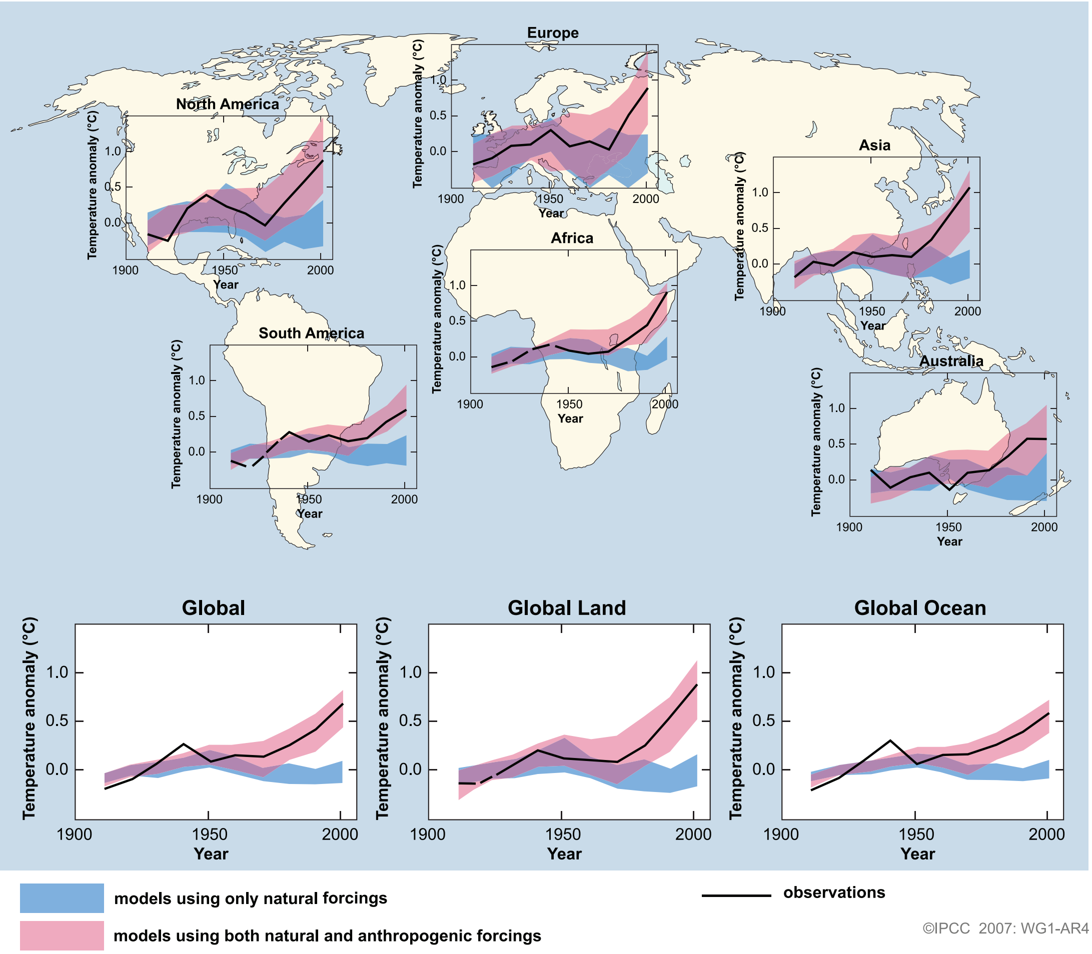


Figure 3.18 Temperature evolution since the year 1900. The black curve in both panels shows the observations, as shown earlier in Figure 3.1. The upper panel shows model simulations with natural and anthropogenic drivers of climate change, where the red curve shows the average across all models and the thin orange lines the individual model simulations. Note that the individual model runs show a random year-to-year variability in global temperature, just like the data. In the model average this is averaged out to a large extent because of its random nature. The lower panel shows model simulations driven only by natural factors, indicating that these cannot explain any warming over the past 50 years or so.



©IPCC 2007: WG1-AR4

Figure 3.19 Comparison of observed and modeled surface temperature changes for different continents and the world. Black lines show observed data. The blue bands show results of a range of climate models using only natural climate forcings such as solar variability and volcanic eruptions. The pink bands show results of a range of climate models if anthropogenic forcings are used together with the natural forcings. Only in the latter case do the models agree with the data, indicating that the observed temperature changes since about the 1970s can only be explained with anthropogenic forcing.

Having said that, how are these formal "attribution" studies performed? To put it simply, observed data from the climate system are compared to what we would expect from natural internal variability (such as random weather fluctuations), from changes in solar activity, from greenhouse gases, or from possible other drivers of climate change. Different drivers of climate change cause different tell-tale patterns of change, so called "fingerprints." Hence, these studies are also known as "fingerprint studies." For example, greenhouse gases tend to trap more heat in the lower parts of the atmosphere, in contrast to a change in solar activity. The effect of greenhouse gases also equally works at night or in winter, while a change in solar activity is obviously more pronounced when the sun actually shines, namely during daytime and summer. Many of these "fingerprint studies" have been performed over the past years by different groups of researchers, using a number of different data sets and statistical approaches.

So what are the results? Those studies analysing global temperature changes have unequivocally come to the conclusion that global warming is indeed to a large part caused by human activities. Global temperatures have already risen beyond their natural range of internal variations, and the observed pattern of changes can only be explained when the effect of rising greenhouse gases is included. That is, the observed patterns are inconsistent with changes in solar activity or any other natural driver of climate change. In fact, natural factors over the past 50 years would have caused a slight cooling of climate, not a warming, due to the observed decline in solar activity (Figure 3.18). Specifically, the report concludes: "It is *very likely* that anthropogenic greenhouse gas increases caused most of the observed increase in global average temperatures since the mid-20th century." (Very likely meaning at least 90% certain.)

Beyond this basic conclusion, attribution studies have come up with a number of other important findings. Not only the surface warming, but also the warming in the free atmosphere above and in the ocean can be attributed to human activities. And not only the global changes, but even the warming in each of the individual continents (except Antarctica) can be attributed to human activities (see Figure 3.19). This is much harder, because natural regional climate variations are much larger than global ones, making it more difficult to prove human-caused changes. A statistically significant human effect has also been found in data other than average temperatures, namely in the decline in sea ice cover in the Arctic, in the rise in sea level, in extreme temperatures, in changing rainfall patterns and in some changes in atmospheric circulation. Taken together, these studies provide a strong confirmation that humans are indeed altering climate in a profound way.

Summary

Measurements unequivocally show that we are in the midst of an accelerating global warming: temperatures have increased on global average by 0.8 °C since the late nineteenth century, and by 0.6 °C since the 1970s. Almost all regions of the planet have warmed over the past century. Both ocean and land areas have warmed, although since the 1970s the land areas have been warming faster. The incidence of extremely hot days is rising, while the number of extremely cold days is declining.

Significant changes in rainfall are also observed. They show a more complex pattern, with some regions showing an increase and some a decrease. Many regions show an increase in the number of days with extreme rainfall amounts, raising the risk of flooding. On the other hand, drought problems are increasing in many parts of the world. The area suffering from drought, according to the widely used Palmer Drought Severity Index, has more than doubled since the 1970s.

In addition, some changes in atmospheric circulation patterns are starting to become apparent. Mid-latitude westerly winds appear to have increased, with storm tracks shifting somewhat towards the poles. The incidence of El Niño events has increased since the 1970s. Finally, tropical storms have shown an increase in intensity and duration since the 1970s.

Many of these observed changes have been shown to be due to human activities by using “fingerprint” analysis.