Chapter 3 Causes of past climate change

The climate of the Earth changes continually on a range of timescales due to 'internal' and 'external' factors. Internal factors are natural and arise from complex interactions within the climate system. In general, internal variability on short time-scales (days to weeks - what we know as 'weather') is generated by atmospheric instability. Variability on longer time-scales (intraseasonal, interannual and decadal to centennial) can be enhanced by complex interactions between the atmosphere and other components of the climate system (mostly the oceans, see e.g. Power *et al*. 1995, but also the terrestrial biosphere and the cryosphere).

Natural external factors include the Earth's rotations that produce diurnal and seasonal cycles, variations in the amount of radiant energy emitted by the Sun (e.g. sunspot cycles have a period of about 11 years), volcanic eruptions and changes in the Earth's orbital parameters (e.g. due to Milankovic cycles, which have a dominant period of 100,000 years). Substantial global warming at the end of ice ages over the past half million years was triggered by changes in the Earth's orbit and subsequently enhanced by natural increases in greenhouse gases.

Humans are also responsible for external factors which are referred to as 'anthropogenic'. For example:

- Changes in atmospheric composition (e.g. in concentrations of stratospheric ozone and greenhouse gases: carbon dioxide, methane, nitrous oxide, chlorofluorocarbons and tropospheric ozone).
- Release of atmospheric particulates (e.g. sulfate aerosols, black carbon).
- Modification of the terrestrial ecosystems (e.g. by land clearance and agricultural practices).

Radiative forcing is the term given to an externally imposed change in the radiation balance (the balance between incoming solar radiation and outgoing heat radiation) such as changes in atmospheric concentrations of greenhouse gases (See section 4.1.3).

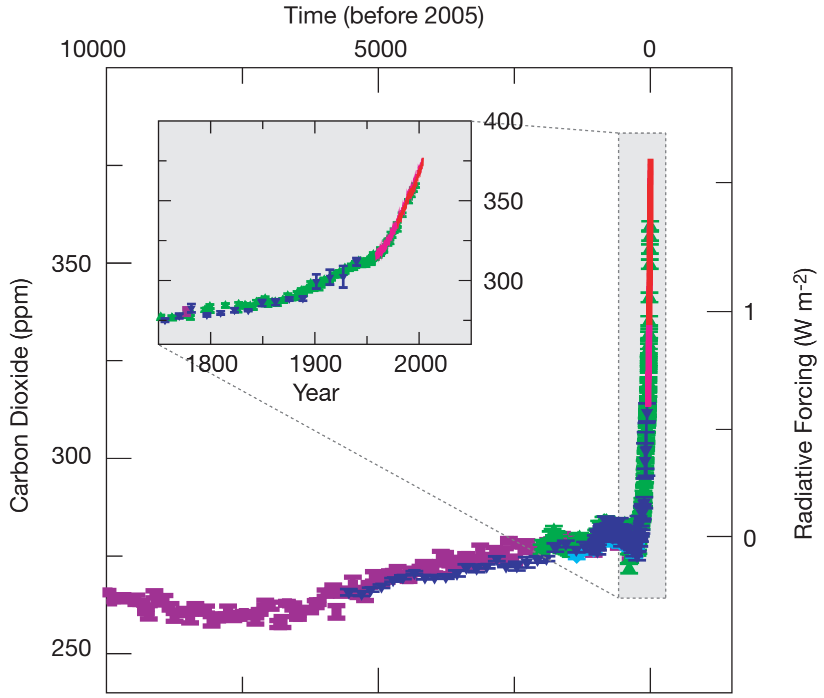

Figure 3.1: Atmospheric concentrations of carbon dioxide over the last 10,000 years (large panel) and since 1750 (inset panel). Measurements are shown for air extracted from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panel (from IPCC (2007a) Figure SPM-1).

The largest change in radiative forcing in the climate system since 1750 has been due to the increase of carbon dioxide (Figure 3.1) followed by an increase in concentrations of other greenhouse gases (IPCC 2007a). There is now "very high confidence level that the globally averaged net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 W/m^2 (with an uncertainty range of +0.6 to +2.4 W/m^2)".

3.1 Detection and attribution of observed climate change

Detection of climate change is "the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change" (IPCC 2001). A change (the 'signal') is *detected* in observations if its likelihood of occurrence by random chance from internal variability alone (the 'noise') is small enough to be regarded as unlikely. To filter out the noise and detect a statistically significant trend, the climate record has to be of sufficient length. 'Sufficient' will vary according to the magnitude of the trend (i.e. smaller signals are harder to detect) and the importance of the noise (i.e. it is more difficult to detect changes in highly variable quantities such as rainfall as opposed to temperature). Because detection studies are necessarily statistical in nature, they are never absolutely certain. Detection does not, by itself, establish the cause of the climate change.

Attribution is "the process of establishing the most likely causes of the detected change with some defined level of confidence" (IPCC 2001). From a practical perspective, IPCC (2001) recommended that attribution of anthropogenic climate change requires:

- The detection of a change to a significant statistical level
- Demonstration that the detected change is "consistent with the estimated responses to the given combination of anthropogenic and natural forcing"; and
- Demonstration that the detected change is "not consistent with alternative, physically-plausible explanations".

Climate models are the major tools used to determine the causes of observed climate change. Climate model simulations can be used to explain recent climatic changes and separate the impact of anthropogenic factors from natural forcings. However, many observed variations are at least partly random in nature and are not expected to be replicated. Indeed, climate models exhibit effectively stochastic (random) behaviour as does the climate system (e.g. Power and Colman 2006). So to attribute a signal in model studies to any external forcing it is a common practice to use an ensemble of several simulations to filter out the naturally occurring internal climate variability within the model from the underlying trends. The differences between simulations reflect the model's estimate of the natural internal variability of the climate system.

Evidence of a human influence on recent climate has accumulated steadily during the past two decades. Despite clear evidence of changes in the composition of the global atmosphere, the first IPCC Assessment Report (IPCC 1990) contained little observational evidence of a detectable anthropogenic influence on climate. However, six years later the Second Assessment Report (IPCC 1996) concluded that "*the balance of evidence*" suggested there had been a "discernible" human influence on the climate of the 20th century. Considerably more evidence accumulated during the subsequent five years, leading the Third Assessment Report (IPCC 2001) to the stronger conclusion that "*most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations*".

More detection and attribution studies were carried out in the subsequent years and the Fourth Assessment Report (IPCC 2007a) concluded that "*most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. Discernible human influences now extend to other aspects of climate, including ocean warming, continental average temperatures, temperature extremes and wind patterns*".

3.2 Attribution of observed climate changes in Australia

3.2.1 Temperature

Australian surface temperatures have warmed significantly over the past century. Warming since the middle of the 20th century is likely to be mostly due to anthropogenic increases in greenhouse gases.

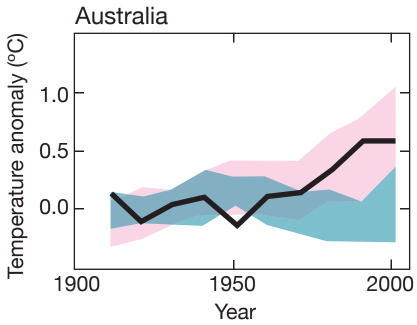

Figure 3.2: Comparison of Australia-wide observed continental changes in surface temperature (black line, decadal averages) with results simulated by climate models using natural only (blue shaded band) and natural plus anthropogenic forcings (pink shaded band). Changes are relative to the average for 1901-1950. Both shaded bands show the 5–95% range of values evident in the simulations (from IPCC (2007a) Figure SPM-4).

Temperature has increased over most of Australia since 1950 (Figures 2.1 and 2.2 and discussion in Chapter 2). As part of the IPCC Fourth Assessment Report, 19 simulations from five climate models from a number of different research groups around the world using only natural forcings and 58 simulations from 14 climate models using both anthropogenic and natural forcings were analysed. Only the ensemble of simulations that includes the anthropogenic forcing in addition to the natural forcing is able to capture the observed warming during the second half of the century (Figure 3.2). The ensemble incorporating natural forcing tracks the decadal averages of the Australia-wide observed temperature only until the 1970s but does not capture the subsequent acceleration of the warming.

This new result confirms an earlier study based on a smaller range of climate models but examining a variety of simple temperature indices. Australian temperature changes over the 20th century appear "very unlikely" to be due to natural climate variations alone, and it was "likely that there has been a significant contribution to the observed warming during the second half of the century from increasing atmospheric greenhouse gases and sulfate aerosols" (Karoly and Braganza 2005a). This work, in turn, advanced earlier work that noted consistency between observed trends and the response of climate models to enhanced greenhouse forcing (Pittock 1988; Power *et al*. 1998b).

It was also demonstrated that the recent increase in temperatures was not a consequence of rainfall change (unlike past changes) and therefore inconsistent with natural climate trends (Nicholls *et al*. 1996; Nicholls 2003; Power *et al*. 1998a,b). Indeed, once the rainfall-related component of the temperature variations is removed, "trends in the residual variations of maximum, mean and minimum temperature over the last 50 years are not explained by natural climate variations and are consistent with the response to increasing greenhouse gases and sulfate aerosols in climate models" (Karoly and Braganza 2005b).

This latter approach is able to enhance the signal-to-noise ratio for anthropogenic temperature change signals in the Australian region and shows that there is a clear anthropogenic warming signal in observed regional temperature trends, even for regions as small as the south-east of Australia. At small regional scales it is not always possible to attribute these regional features to a specific cause as more than one factor may be contributing to the change in the climate. An exception is the central part of the south-east of Australia which has warmed during the second half of the 20th century but by a much smaller amount than the rest of the continent. This reduced rate of warming was related to changes in the Southern Annular Mode. (Hendon *et al*. 2007).

3.2.2 Rainfall

The rainfall decrease in south-western Australia since the mid-1970s is likely to be at least partly due to anthropogenic increases in greenhouse gases. It is not yet possible to attribute rainfall decreases in eastern Australia, and rainfall increases in north-western Australia to human activities.

The possible causes of the rainfall decrease in the south-west of Western Australia in the mid-1970s have been studied extensively (Ryan and Hope 2005, 2006). The rainfall decline has been related to changes in the large-scale winter weather systems that bring rain to south-west Western Australia. The number of synoptic weather patterns that bring wet conditions decreased in the mid-1970s accompanied by an ongoing increase in the number that bring dry conditions (Charles *et al*. 2004). This reduction in June and July has contributed 50% of the rainfall decline in the mid-1970s (Hope *et al*. 2006). Changes in the convergence of moisture into the region by the wind also contribute to the rainfall decline (Timbal 2004). On a broader scale, a drop of 20% in the strength of the upper level winds has lead to a reduction in the likelihood of storm development over south-west Western Australia compared to the pre-1970s (Frederiksen and Frederiksen 2007). Although climate model simulations can occasionally produce a decline as substantial as that observed in the south-west without changes in external forcings (Cai *et al*. 2005b), the consensus is that "it is unlikely that the observed drying is a result of natural fluctuations in the climate" (Ryan and Hope 2006), and it is likely that the natural fluctuations inherent in the climate system and changes in greenhouse gas concentrations have contributed to the observed rainfall decline in south-west Western Australia (Timbal *et al*. 2006). Averaging over all IPCC (2007a) model simulations, it is found that 50% of the reduction is attributable to anthropogenic forcing that has a structure that is reminiscent of the Southern Annular Mode (see Chapter 5) and its impact on rainfall in south-west Western Australia (Cai *et al*. 2003a; Cai and Cowan 2006, 2007). The role of land cover changes is recognised as a possible secondary contributor but is unlikely to be the major factor in the rainfall reduction over south-west Western Australia (Pitman *et al*. 2004; Timbal and Arblaster 2006).

The more recent rainfall decline in the east of the continent (see Figure 2.5 and Chapter 2) is only now being studied extensively and is yet to be attributed to external causes (Nicholls 2006). However, the rainfall decline in the south-east of South Australia and the south-west of Victoria bears some characteristics consistent with the earlier rainfall decline in the south-west of Western Australia and has similarly been linked to large-scale changes in mean sea level pressure (Timbal and Jones 2007). The fact that the change is occurring much later may be due to the movement of the subtropical ridge (Drosdowsky 2005). However, the rainfall decline in this part of the continent appears more complex. In particular the influence of the tropical Indian Ocean is important (Meyers *et al*. 2007) but appears to have disappeared during the recent dry decade, possibly as a consequence of the increase of mean sea level pressure across the southern half of the continent (Timbal and Murphy 2007).

The largest rainfall trend observed in Australia is the increased summer rainfall in the north-west of the continent (see Figure 2.4 and Chapter 2). The attribution of these changes remains an important area of research. Two factors that are potentially relevant have been identified: warming of the Australian continent might have helped to drive to a strengthening of the monsoon, resulting in increased rainfall (Wardle and Smith 2004); and an increase in anthropogenic aerosols in the atmosphere in the latter part of the 20th century predominantly linked to extensive haze of much of Asia might have altered atmospheric circulation over northern Australia (Rotstayn *et al*. 2007). Further work on these and other possible causes are required.

3.2.3 Drought

Droughts have been accompanied by higher temperatures due to anthropogenic warming.

Recent Australian droughts (1994, 2002-03 and 2006-07) have not become drier than droughts that occurred earlier in the 20th century. However, the recent droughts have been accompanied by higher temperatures (Nicholls 2004; Murphy and Timbal 2007).

The distinction between 'meteorological drought' (due to rainfall deficiency) and other forms of drought, e.g. agricultural drought or hydrological drought, is sometimes made (see Chapter 5 for further details). It is possible, for example, that a given region might be experiencing an agricultural drought even if the criteria used to define meteorological drought have not been met. For example, seasonal rainfall might be near-average but the rain did not fall during the times when it was needed by the crop. Factors other than just rainfall can also be influential in determining non-meteorological drought. It is possible, for example, that in some contexts a temperature rise might increase the water required by the crop to grow. Warming might therefore intensify agricultural drought in a region where the crop is very common. As most of the observed warming in Australia since 1950 can be attributed to human-induced increases in greenhouse gases (section 3.2.1; IPCC 2007a) the severity of agricultural drought in that region could then be partly attributed to anthropogenic warming. While this is a plausible scenario, very little research has been done to date on either the quantification of trends in drought severity in its various forms beyond simply using rainfall deficit, or in the cause of any observed trends.

3.2.4 Snow

The decline in snow cover observed in recent decades is probably due to anthropogenic warming.

The snow season in the Australian Alps has shortened in recent decades, with less snow remaining early in spring This is due to warming (i.e. more precipitation falling as rain rather than snow, and earlier melting of snow on the ground) rather than any substantial decline in precipitation (Nicholls 2005). Since most of the observed warming in Australia since 1950 can be attributed to human-induced increases in greenhouse gases (IPCC 2007a), it can be inferred that most of the decline in snow cover is also due to human activities.

3.2.5 Changes in seasonal cycle

Little work has been done to investigate trends in indicators of seasonality. One exception, for rainfall, is the timing of the 'autumn break' or start of the wet season in northern Victoria which is largely determined by the occurrence of cut-off low pressure systems (low pressure systems that have separated from the circumpolar westerlies further south). Over the past decade, the autumn break is occurring later than previously or is failing to occur at all (Pook *et al*. 2006). The attribution of this change has not yet been made.

For temperature, it was found that the warmest time of the year in south-east Australia is occurring about a week later now than at the start of the 20th century (Alexander *et al*. 2005). No studies have yet attempted to attribute these changes to particular external causes.

3.2.6 Extremes

There has been an increase in the frequency of warm days/nights and a decrease in the frequency of cool days/nights. It is likely that these changes are mostly due to anthropogenic warming.

It is not possible to attribute a single extreme event to any particular external forcing; however, the trend in the frequency of extremes is potentially attributable to external causes (see Box 3.1). Extreme temperatures have changed in Australia, with a tendency for increased numbers of warm days and nights and fewer cool days and nights (Figure 2.3; Nicholls and Collins 2006; Alexander *et al*. 2007). This result is similar to what has been observed throughout eastern Asia and western Pacific (Griffiths *et al*. 2005). The frequency of extremes is affected by changes in mean temperatures (Griffiths *et al*. 2005), and given that regional-scale mean temperatures are likely to have changed as a result of human influence on the climate system, it is reasonable to conclude that the changes in frequency of extremes in Australia can also be partly attributed to human factors.

Extremes in daily rainfall also display trends in the same direction as the mean rainfall trends, however, the trend in the extremes is often greater than for the mean, indicating that the frequency of extreme events is changing faster than the mean (Alexander *et al*. 2007).

3.2.7 Other modes of variability

Most attribution studies have concentrated on secular trends, but considerable research also has been carried out to determine the causes of interannual and interdecadal variations in the Australian climate. Many of these studies have focussed on the effects of the El Niño – Southern Oscillation on Australian rainfall and temperature (e.g. Power *et al*. 1999, 2006; Meinke *et al*. 2005). Some studies also investigated the impact of variations in the Indian Ocean sea surface temperature on interannual variations of the Australian climate (Cai *et al*. 2005a; Meyers *et al*. 2007) and the impact of the Southern Annular Mode on the Australian climate (Cai and Cowan 2006; Hendon *et al*. 2007; Meneghini *et al*. 2007). Such seasonal-to-interannual variations are most likely the result of internal natural variability of the climate system.

3.2.8 Oceans

Rapid warming in the Tasman Sea is likely to be driven by Antarctic ozone depletion through an upward trend of the Southern Annular Mode.

Climate change in the oceans surrounding Australia is less definitive than over the land, due mainly to the shorter period for which observations are available. While some changes are evident, it is difficult to attribute the cause or the link to anthropogenic forcing.

One exception is the fast warming rate off Tasmania's Maria Island, where continuous ocean temperature measurements since the late 1940s exist and which reveal a trend that is three times greater than the global warming rate. Warming off Maria Island since the late 1970s represents a fast Tasman Sea warming rate and is principally driven by Antarctic ozone depletion. Ozone depletion causes the atmospheric circulation to change in a way that is reminiscent of changes linked to a positive phase of the Southern Annular Mode (Cai 2006; Cai and Cowan 2007). Thus both internal and external forcing can drive Southern Annular Mode-like features to the atmospheric circulation over the southern hemisphere. Ozone depletion as a result of human activities also causes circulation changes in the stratosphere, largest during the spring months, with a strengthening of the circumpolar westerlies and a weakening of the mid-latitude westerlies closer to the surface. These wind changes are largest during summer (Thompson and Solomon 2002; Gillett and Thompson 2003; Miller *et al*. 2006; Cai and Cowan 2007), when the East Australian Current is strongest and extends furthest to the south. The wind changes drive a stronger East Australian Current, moving more warm water south, leading to the warming in the Tasman Sea.

Box 3.1 Can individual extreme events be explained by climate change?

A wide range of extreme weather events is possible even in an unchanging climate, so it would be difficult to attribute an individual event, by itself, to a changed climate. Extreme weather results from a combination of factors. For example, the formation of a tropical cyclone requires a warm sea surface and specific atmospheric circulation conditions. Because some factors may be strongly affected by human influences (e.g. sea surface temperatures) but others may not, this will complicate the detection of a human influence on a single, specific extreme event.

However, it may be possible to determine whether anthropogenic forcing has changed the probability of occurrence of a specific type of extreme weather event. The value of a probability-based approach ("is there a change in the likelihood of an event that results from human influence?") is that it can be used to estimate the influence of external factors, such as increases in greenhouse gas concentrations, on the frequency of specific types of weather events (e.g. frosts, heatwaves, heavy rainfalls or floods). A climate model, either forced only with historical changes in natural factors such as volcanic activity and solar output, or by both human and natural factors, can be used to indicate whether, over the 20th century, human influences have increased the risk of any type of extremes. However, careful statistical analyses are required, since the likelihood of individual extremes could change due to changes in variability as well as changes in the mean climate. Such analyses rely on climate model-based estimates of variability, and thus an important additional requirement is that climate models adequately represent climate variability.

Global warming can increase the likelihood of a record high temperature in a given region. This means that a record high temperature that may seem extraordinary in an unchanging climate seems less extraordinary if global warming is taken into account (Power and Nicholls 2007).

In the future, climate model simulations project that there will be changes in the incidence of many types of extreme weather events, including an increase in extreme rainfall events, due to human influences on the atmosphere (IPCC 2007). There is evidence of increases in extreme rainfall events in at least some regions in recent decades. However, there is as yet no conclusive evidence that these increases are necessarily linked to increasing greenhouse gas concentrations.