indicates that Greenland was largely deglaciated at this time, with ice restricted to high-altitude regions of East Greenland (Lunt et al., 2008). Margins of the East Antarctic Ice Sheet may also have retreated, especially in the Wilkes sub-glacial and Aurora basin sectors (Hill et al., 2007). Recent climate and ice-sheet sensitivity studies have indicated that the most important forcing in driving a largely deglaciated Greenland at this time was the higher than pre-industrial levels of CO₂ (Lunt et al., 2008).

Pollen records and other plant remains from around the world indicate large changes in biomes compared to today. For example, the extent of arid deserts appears to have been greatly reduced. Tropical savannah and woodlands were extended and coniferous forests replaced tundra in the northern hemisphere (Salzmann et al., 2008).

Geological proxies for sea surface temperature (SST) indicate that the mean state of the eastern equatorial Pacific (EEP) may have been 2–3 °C warmer than modern, substantially reducing the SST gradient between the west and the east Pacific to a situation similar to that which occurs during a modern El Niño event (Wara et al., 2005). Owing to the temporal resolution of the data sampling, it is not possible to obtain information on the interannual variability of the SST, hence the period has been characterised as displaying a permanent El Niño-like mean state, or El Padre to differentiate it from a modern El Niño (Ravelo, 2008).

Coupled ocean–atmosphere climate models are able to reproduce a reduced SST gradient across the Pacific and warmer EEP SSTs (Haywood et al., 2007; Figure 2.2), but still display SST variability over ENSO timescales. Predictions from the Hadley Centre coupled climate model version 3 (HadCM3), show that the frequency and magnitude of El Niño events differed from today (i.e. became more frequent and stronger), suggesting that the warmer EEP SSTs may not have been caused by a perennial El Niño condition (Bonham et al., 2009; Wünsch, 2009; Figure 2.2). The reason why ENSO frequency changed is currently being explored.

While ENSO is the best known and strongest of the ocean–atmosphere interactions leading to year-to-year differences in climate conditions, several other such systems are also recognised. These include the North Atlantic Oscillation (NAO), Polar Vortex, Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM). Recent research indicates that climate change may interact with these ocean–atmosphere modes of climate variability. These systems influence patterns of temperature and rainfall on inter-annual timescales. Also seasonal changes in rainfall and temperature (i.e. monsoon systems) can, however, be driven by ocean–atmosphere interactions. Common for many of these ocean–atmosphere interactions is that the phenomena may be affected by climate change in ways that drive a larger amplitude in climate fluctuations in coming decades (Box 2.2).

**Box 2.2**

**Changing modes of ocean–atmosphere variability**

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While ocean heat uptake significantly buffers the magnitude of anthropogenic warming of the atmosphere (Levitus et al., 2001), there are major risks associated with this ocean warming. Apart
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from raising sea levels (Box 1.3 and Chapter 3), changing the ocean’s thermohaline circulation (Chapter 7) and reducing carbon uptake (Chapter 4), ocean surface warming will also alter coupled ocean–atmosphere modes such as El Niño. Other ocean–atmosphere modes of variability are also likely to be affected, including the Indian Ocean Dipole. This will occur as human-induced warming directly changes the temperature of the surface mixed layer and also alters the ocean’s thermocline depth; both are key properties that determine the magnitude, nature and frequency of coupled ocean–atmosphere modes of variability. The higher latitude modes of variability will also be affected, such as the North Atlantic Oscillation and the Southern Annular Mode, although these modes will primarily be altered via an internal atmospheric response to increased greenhouse gases and depleted polar stratospheric ozone. Changes in these major hemisphere-scale patterns of variability will significantly impact regional climate, such as mid-latitude rainfall rates. Figure 2.3 shows an overview of the major climate modes and their projected trends.

Model projections (Chapter 7) suggest that anthropogenic climate change will force El Niño events to drift toward a different preferred state in coming decades (Latif and Keenlyside, 2008; Yeh et al., 2009). There is even some evidence that change is already underway – with several studies noting a greater number of ‘central’, as opposed to ‘eastern’, Pacific El Niño events occurring in recent years (see Ashok et al., 2007; Taschetto and England, 2009). One such central Pacific event occurred in 2002–03 when ocean warming developed most markedly in the central equatorial Pacific instead of in the east, which is atypical for ENSO episodes. The anomaly pattern has been tentatively classified as an independent mode, termed the El Niño ‘Modoki’ (or pseudo-El Niño). This mode is characterised by warmer than usual central Pacific waters and associated cooler SST anomalies on the eastern and western portions of the basin (Ashok et al., 2007). While the peak Pacific warming in 2002–03 was only modest, the rainfall

Figure 2.3 Schematic diagram showing the major modes of climate variability and how they are likely to change in the future. The high-latitude modes have already undergone significant change over the past century. Trends in the tropical modes (ENSO, IOD) have been detected in the more recent climatological record. (Full version of this figure in colour as Plate 4.)

Box 2.2 (cont.)
response in some regions was significant. For example, eastern Australia experienced some of its most severe reductions in rainfall during this Modoki event. This unusual El Niño event has raised questions as to exactly how regional rainfall is controlled by the location and magnitude of tropical Pacific SST variability, and importantly how this will be transformed in the future.

A major coupled mode of Indian Ocean variability also appears to be changing, with a reported increased incidence of positive phase Indian Ocean Dipole events over the last few decades (Abram et al., 2008; Cai et al., 2009). This coincides with recent non-uniform warming trends in the Indian Ocean (Alory et al., 2007; Ihara et al., 2008), which have likely affected the average background climate of the region. Like shifts in El Niño, this could have significant impacts on regional climate if the trend continues, affecting rainfall over East Africa (Latif et al., 1999; Black et al., 2003), India, Indonesia (D’Arrigo and Wilson, 2008), and Australia (England et al., 2006; Ummenhofer et al., 2008).

While trends are becoming evident in the coupled climate modes in the observational records, it remains unclear how these trends will evolve over the coming century. It is, for example, unclear how El Niño and the Indian Ocean Dipole will be influenced by the emergent changes in the large-scale meridional and zonal circulation of the atmosphere (e.g. the Hadley and Walker circulations). Regardless, against the background of ongoing ocean warming and continuing trends in the large-scale atmospheric circulation, it is highly likely that the major coupled ocean–atmosphere modes of variability will change significantly in the future, with unknown consequences for regional rainfall and climate.

The most prominent feature of variability in the extratropical regions is the so-called annular modes in both hemispheres, which regulate the latitude of the polar front jets and subpolar westerly winds. In the south is the Southern Annular Mode, a pressure oscillation between Antarctica and the subtropical high pressure belt, which controls variations in the strength and latitude of the subpolar westerly winds. In the north is the Northern Annular Mode, which is linked closely to the North Atlantic Oscillation (Visbeck et al., 2001); the latter is effectively a regional manifestation of the circumpolar annular mode. These extratropical oscillations are largely internal (uncoupled) modes of atmospheric variability, controlled by interactions between the mean and transient atmospheric circulation; in particular the mid latitude cyclones. The annular modes exhibit significant variability on synoptic, seasonal and interannual timescales. Yet as climate change is impacting both the mean state of the atmosphere and the transient eddies at mid latitudes, the annular modes are also undergoing change, gradually contracting toward a more poleward mean position, particularly in the southern hemisphere.

This is having a significant impact on regional weather systems and mean climate. For example, over the southern hemisphere, the frequency of extratropical low pressure systems in the latitude band 40 °S to 60 °S has decreased over the past few decades. This has been linked to both increasing greenhouse gases (Fyfe, 2003) and depleted stratospheric ozone (Gillett and Thompson, 2003); these two anthropogenic causes have combined to force a poleward shift in the southern hemisphere polar front jet. This significant adjustment in the extratropical regions is already having a profound impact on regional climate; for example, affecting drought over parts of Australia (Cai and Cowan, 2006). Furthermore, this trend is projected to continue as greenhouse gas concentrations rise this century (Sen Gupta et al., 2009), with a similar shift likely for the Northern Annular Mode. Such a change in the atmospheric circulation in the extratropical regions would have a profound impact on regional rainfall and climate.