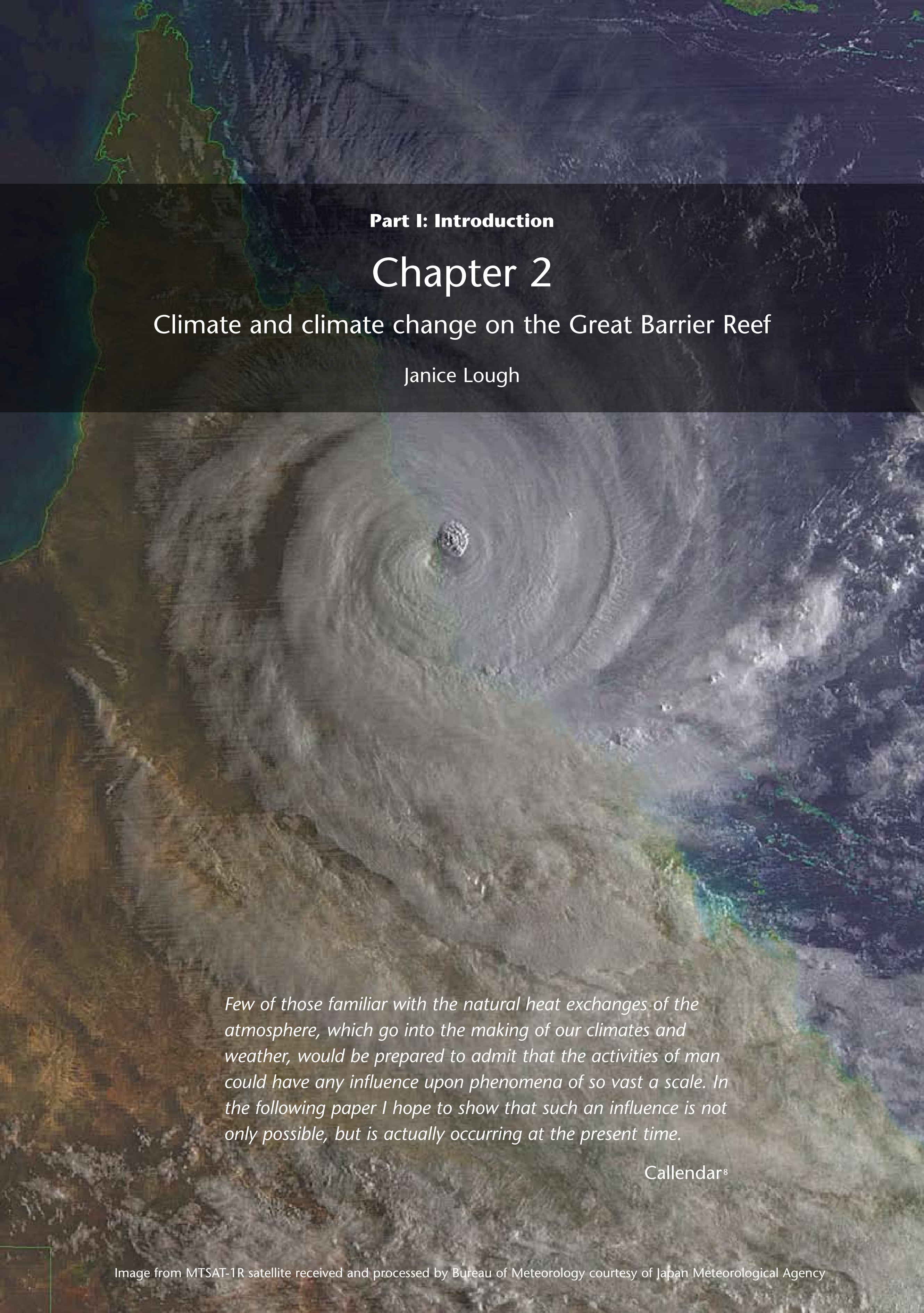
Part I: Introduction

Chapter 2

Climate and climate change on the Great Barrier Reef

Janice Lough



Few of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climates and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale. In the following paper I hope to show that such an influence is not only possible, but is actually occurring at the present time.

Callendar[8]

Image from MTSAT-1R satellite received and processed by Bureau of Meteorology courtesy of Japan Meteorological Agency

2.1 Introduction

The expectation of climate change due to the enhanced greenhouse effect is not new. Since Svante Arrhenius in the late 19th century suggested that changing greenhouse gas concentrations in the atmosphere could alter global temperatures[3] and Callendar[8] presented evidence that such changes were already occurring, we have continued conducting a global-scale experiment with our climate system. This experiment, which began with the Industrial Revolution in the mid 18th century, is now having regional consequences for climate and ecosystems worldwide including northeast Australia and the Great Barrier Reef (GBR).

This chapter provides the foundation for assessing the vulnerability of the GBR to global climate change. This chapter outlines the current understanding of climate change science and regional climate conditions, and their observed and projected changes for northeast Australia and the GBR.

2.2 A changing climate

*The last five years have seen a rise in observable impacts of climate change, especially those, such as heatwaves that are directly related to temperatures. The impacts of rising temperature on the Earth's biodiversity are also now well documented and there is some circumstantial evidence for an increase in storms, floods and other extreme events as well as in the intensity of tropical cyclones. Adaptation to climate change is no longer a question of **if** but now of **how**, **where**, and **how fast**.*

Steffen[57]

2.2.1 Weather and climate

Weather is the state of the atmosphere at a given time and place as described by variables such as wind speed and direction, air temperature, humidity and rainfall. Climate is what we expect the weather to be like at a particular time of year and place, based on many years of weather observations (30 years has typically been used by the World Meteorological Organization to define climate 'normals')[a]. The climate of a region includes both long-term averages of the various weather elements and their variability about the averages (ie observed range of extremes, standard deviation). Surface climate of northeast Queensland and the GBR is, therefore, defined by what we expect the air temperatures, sea surface temperatures, rainfall, river flow, wind speed and direction, occurrence of tropical cyclones and ocean currents to be like at any given location and season.

2.2.2 Climate variability and change

Global climate has varied on a range of time and space scales. For example, climate variations over hundreds of thousands of years between glacial and inter-glacial conditions due to changes in Earth's orbital position[5]; and spatial differences allowing classification of Australian climate zones[59]. Current climate conditions in the vicinity of the GBR were established after the end of the last ice age

---

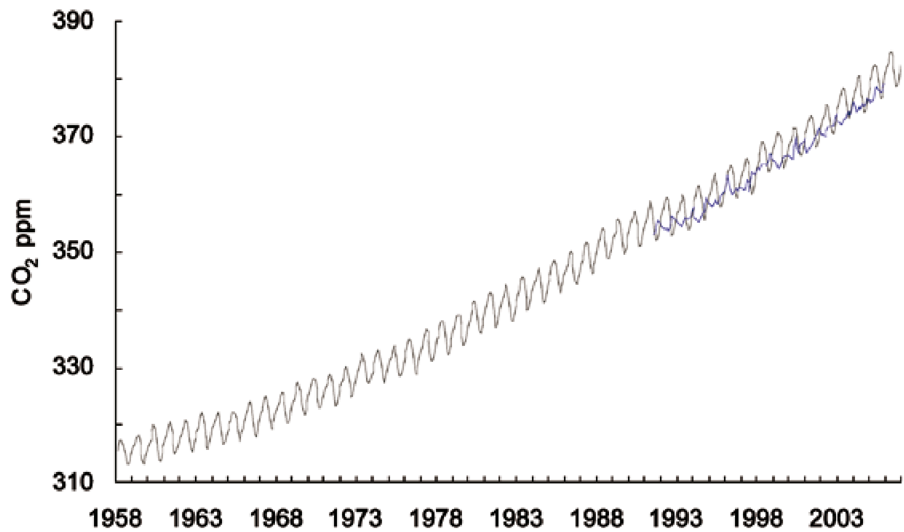
a American Meteorological Society

with current sea level being reached about 6000 years ago. Climate varies naturally due to various factors that are internal and external to the complex climate system (consisting of the interacting atmosphere, oceans, biosphere, land surface and cryosphere) including feedbacks that can amplify or dampen an initial disturbance, variations in solar and volcanic activity, but usually within the range of observed average climate and its extremes. A climate change occurs when there is a significant change in average climate and/or its variability with the consequence that our expectation of what the weather will be like also changes.

2.2.3 Global climate change

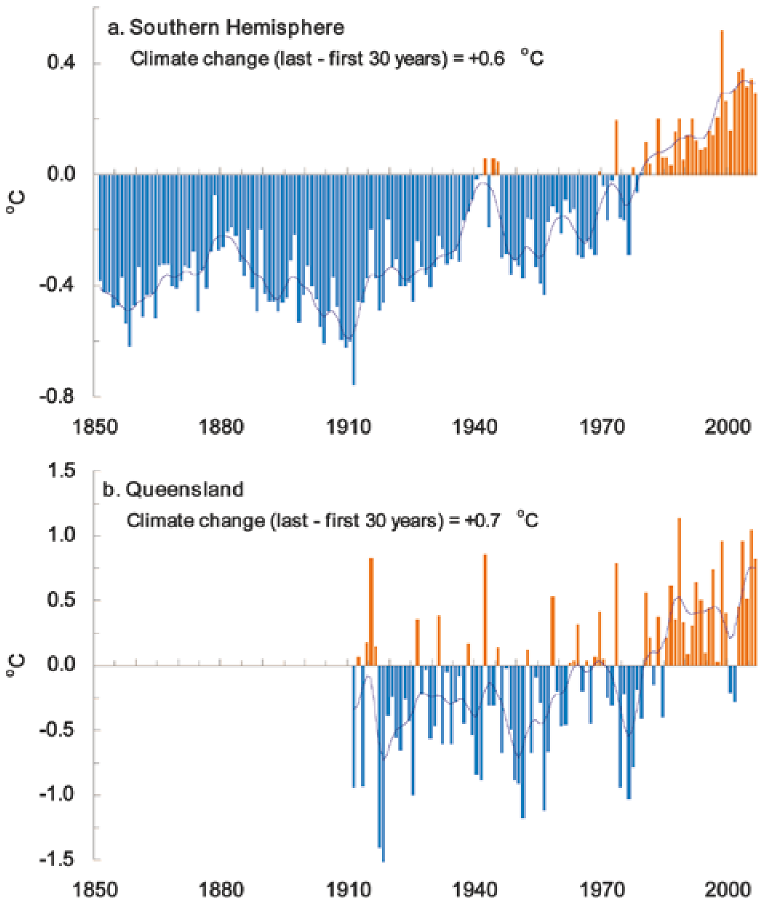
Human activities since the Industrial Revolution in the mid-18th century have increased the atmospheric concentration of greenhouse gases. These gases are present naturally in our atmosphere and without this 'natural' greenhouse effect the Earth would be about 30°C cooler with conditions inhospitable to life, that characterise Mars and Venus. The increased concentration of greenhouse gases (the enhanced greenhouse effect) essentially traps more heat in the global climate system and causes *global warming* (Figure 2.1). There is now no scientific doubt that human activities have changed the composition of the atmosphere and the oceans[24]. The change in the heat balance of the earth is now causing observed changes in global and regional climate[23,24] (Figure 2.2).

Figure 2.1 *Monthly atmospheric concentrations of carbon dioxide (CO_2) for Mauna Loa, Hawaii (grey, 1958 to 2006) and Cape Ferguson, Queensland, Australia (blue, 1991 to 2005) illustrating the well-mixed nature of this atmospheric gas with local trends matching global trends and the steady increase in atmospheric concentration of the major greenhouse gas attributable to human activities. (Data source: World Data Centre for Greenhouse Gases[b])*



b http://gaw.kishou.go.jp/wdcgg.html

Figure 2.2 *Instrumental October to September anomalies from 1961 to 1990 mean for a) Southern Hemisphere air and sea temperatures, 1851 to 2006 and b) Queensland air temperatures, 1911 to 2006. Thick line is 10-year Gaussian filter emphasising decadal variability. The two series are significantly correlated, 1911–2006, r = 0.66. (Data sources: HadCRUT3, Climatic Research Unit, UK, Brohan et al.[7]; Australian Bureau of Meteorology, Lough[33])*



2.2.4 Future climate change and uncertainty

Projecting the global and regional consequences of the enhanced greenhouse effect is a complex problem. Solving this problem relies on adequate understanding and modelling of past and current climate conditions, the factors responsible for maintaining these conditions and the factors that drive changes in climate. Modelling how climate will change in an enhanced-greenhouse world also depends on projecting how greenhouse gas concentrations will change in the future. This depends on a variety of socio-economic factors such as population growth, levels of affluence, intensity of energy use and the strategies implemented to reduce future emissions (mitigation). Hence, there is no single future climate scenario for a doubling of atmospheric greenhouse gas concentrations, but rather a range of possible futures that depend on human factors (Appendix 2.1 Special Report on Emissions Scenarios (SRES) storylines[46]), climate sensitivity, responses and feedbacks and the ability of different climate models to faithfully simulate climate[23,65,69]. These plausible projections of future climate conditions contain two major sources of uncertainty. Firstly, uncertainty due to differences between individual climate models because of incomplete understanding of the physical processes of the climate system and how they work together and interact. Secondly, uncertainties due to different assumptions and projections of future greenhouse gas concentrations. Our ability to project and assess the regional consequences of global climate change and, thus locally relevant impacts, depends on our ability to realistically downscale global climate projections. The coarse spatial resolution used in current global climate models does not provide this local-scale weather and climate detail and several (downscaling) techniques are used to provide regional climate information based on the large-scale climate conditions produced by global climate models[71]. Current limitations in local-scale climate projections[69] add therefore, another level of uncertainty (and increases the range of possible future climate conditions) in assessing climate change impacts (Figure 2.3).

Regional projections of temperatures for northeast Australia and the GBR have greater certainty than those for rainfall and river flow. This is because:

1) Regional rainfall may either increase or decrease in future whereas temperature will increase,

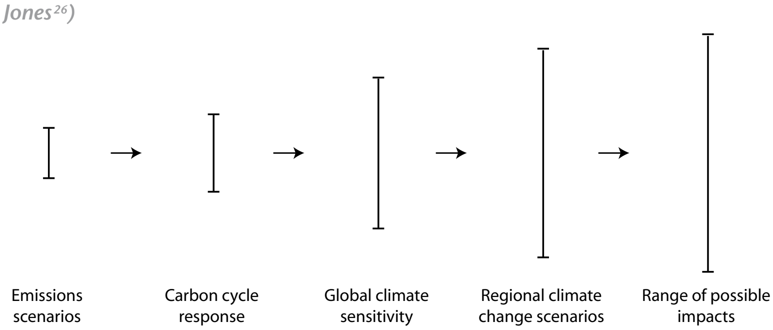
2) There is greater variability of rainfall compared to temperature making the potential greenhouse signal weaker, and

3) There is poorer spatial representation of rainfall in climate models and their poor ability to correctly simulate present-day Australian monsoon rainfall[45,69].

There is also no clear consensus as to how El Niño-Southern Oscillation (ENSO) events will change as global climate continues to warm.

There is, therefore, a range of uncertainties in projecting exactly how surface climate in northeast Australia and the GBR will change over the coming decades and century. It is clear, however, that we are committed to major global and regional climate change and that some climate variables have already shown statistically significant changes. Even if all greenhouse gas emissions were halted now, we are still committed to further significant climate change (0.1°C per decade compared with current projections of 0.2°C per decade) and sea level rise[43,70,24].

Figure 2.3 *'Explosion of uncertainty' in assessing the impacts of global climate change. (Source: Jones[26])*



2.2.5 Current projections

The most recent projections of global climate change due to the enhanced greenhouse effect suggest global average temperature could warm by 1.1 to 6.4°C over 1980 to 1999 values by 2100[24] with best estimates ranging from 1.8 to 4.0°C. These are generally consistent (although not strictly comparable) with the earlier projections of 1.4 to 5.8°C[23] and are based on more climate models of greater complexity and realism and better understanding of the climate system. These projections are for global average temperatures and contain significant geographic variations with greater warming in high latitudes compared to lower latitudes and greater warming in continental interiors compared to ocean areas. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report[24] also presents new and stronger evidence compared with the Third Assessment Report[23] that 'warming of the climate system is unequivocal', that there is 'very high confidence' that this warming is the net effect of human activities since the Industrial Revolution, and that most of the observed global warming since the mid-20th century is 'very likely' due to the observed increases in greenhouse gas concentrations. There is also mounting evidence of changes in the biosphere (even with the relatively modest climate changes observed to date) with alterations in migration patterns, distributions and seasonally-cued cycles observed in various marine, terrestrial and freshwater species all occurring in a direction that is consistent with a warming climate[6,22,44,50].

2.2.6 Evidence for recent warming

Compilations of instrumental global land and sea temperatures back to the mid-19th century provide strong evidence of a warming world and the recent unusual warmth, with nine of the 10 warmest years since 1850 occurring between 1997 and 2006[7,17c,24]. For Australia, 2005 was the warmest year on record with annual average temperatures 1.1°C above the 1961 to 1990 mean and average daily maximum temperatures 1.2°C above average. April 2005 witnessed the largest Australian monthly temperature anomaly ever recorded in the period back to the early 20th century, 2.6°C above the 1961 to 1990 average. The global and regional warmth of 2005 is of particular significance as there was no ENSO event. This contrasts with the exceptional warmth of 1998, by some measures the warmest year on record, when the major 1997 to 1998 ENSO event significantly contributed to above average temperatures[57] (Bureau of Meteorology[d]).

2.3 Current surface climate

Average seasonal surface climate in northeast Australia and the GBR is dominated by two large-scale global circulation systems, the south-easterly trade wind circulation and the Australian summer monsoon westerly circulation[60]. These effectively divide the year into the warm summer wet season (October to March) and the cooler winter dry season (April to September). This seasonality makes the 12-month 'water year', October to September, the most appropriate annual average rather than the calendar year. Tropical cyclones are an important feature of the summer monsoon circulation and can occur on the GBR between November and May with peak activity January to March[53].

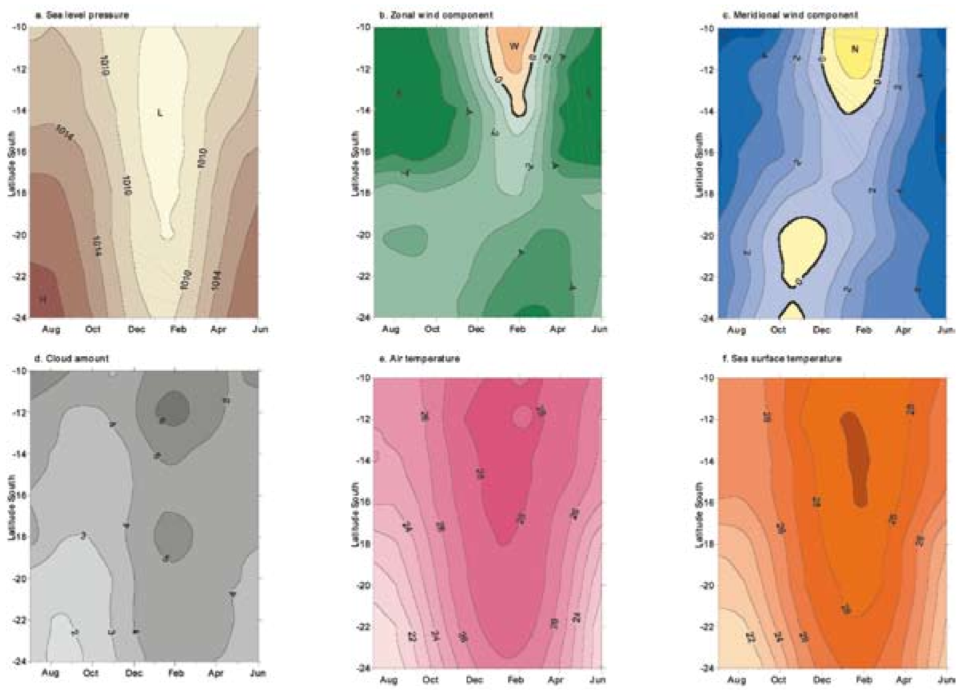
c http://www.cru.uea.ac.uk/cru/info/warming/

d http://www.bom.gov.au

2.3.1 Atmospheric circulation

Average monthly variations of the atmospheric circulation along the GBR (Figure 2.4) show the seasonal intrusion of the summer monsoon circulation[38,61]. This brings lower sea level pressure, greater cloud amount and weaker, moister, more westerly and northerly surface winds than found in winter. These features are most marked in January and February. Although the 'monsoon' circulation features only extend to 14 to 15° S, they introduce strong seasonality into the rainfall and river flows adjacent to the GBR. The summer monsoon displaces the belt of south-east trade winds southward in summer. In winter, much of the GBR is influenced by anticyclonic conditions, which have a more northerly location over Australia at this time of year[60]. The largest month-by-month changes in circulation typically occur from October to November although the onset of the summer monsoon does not usually occur until mid-December[18]. The monsoon retreats from about March to April. A characteristic of climate in low-latitude Australia and ENSO is the high persistence of circulation anomalies from late winter to early summer and low persistence from late summer to autumn[1,42].

Figure 2.4 *Monthly and latitudinal variations of average (1950 to 1997) climatic variables along the GBR for a) sea-level pressure (millibar); b) zonal wind component (metres per second, negative values indicate easterly winds; c) meridional wind component (metres per second, positive values indicate southerly winds); d) cloud amount (oktas); e) air temperature (°C); and f) sea surface temperature (°C). (Data source: NCAR/NOAA Comprehensive Ocean Atmosphere Data Set (COADS)[e], Woodruff et al.[73])*



e http://www.dss.ucar.edu/pub/COADS_intro.html

2.3.2 Air and sea surface temperatures

Monthly mean air and sea surface temperatures (SST) show a similar distribution with annual maxima from January to February and minima in August. Greatest seasonal warming of SSTs occurs from October to September (1.4 to 1.7°C) and greatest seasonal cooling from May to June (1.1 to 1.8°C). SSTs tend to be warmer than air temperatures throughout the year, the difference being greater in winter than in summer. Monthly mean SSTs range from greater than 29°C in summer in the north to less than 22°C in winter in the south. The annual range of SSTs is approximately 4°C in the north and approximately 6°C in the south. The variability of monthly SSTs (standard deviation) is typically 0.4 to 0.6°C and is similar for different months and latitudes. The range between maximum and minimum SSTs is 2 to 3°C. These statistics are based on large-scale averages and the range of SST variability observed on coral reefs can be much greater. For example, at the offshore Myrmidon Reef automatic weather station[f], the average diurnal SST range is 1°C and average daily SSTs vary between a minimum of 24°C in the last week of August to a maximum of 29°C in the first week of February (4.8°C range). The difference between the observed daily maximum and minimum SSTs is 9.5°C. Thus, the range of SSTs experienced by tropical marine organisms is much larger than the 2 to 3°C obtained from the large-scale monthly statistics. These large-scale averages also disguise the tendency for SSTs in inshore, shallower waters to be warmer in summer and cooler in winter compared to offshore deeper waters. Despite differences in absolute average SSTs along the GBR, SST anomalies (ie unusually cool or warm waters) tend to vary coherently throughout the region indicating strong, large-scale controls[30,34].

2.3.3 Rainfall

The summer monsoon circulation brings the majority of the annual rainfall to northeast Australia with approximately 80 percent of the annual total occurring in the summer half year[32,33]. Rainfall is, however, highly variable within the summer monsoon season and usually occurs in several bursts of activity often linked to the progression of the 30 to 60 day Madden Julian Oscillation[19,18,61]. Rainfall typically occurs on only 30 percent of days in summer and only 14 percent of days in winter. There is also considerable inter-annual variability in rainfall. At Townsville, for example, median October to September rainfall over the period 1941 to 2005 was 1036 mm, with 86 percent of the total occurring in the summer half of the year. The wettest year was 1974 with 2158 mm (more than twice the long-term median) and the driest year was 1969 with 398 mm. All months from April to December have experienced no rainfall in some years and even for the wettest months, January to March, minimum monthly rainfall was less than 10 mm. Due to the high spatial and temporal variability of rainfall, the long-term average is not a good guide to the amount of rainfall that can be expected. The median is a more appropriate statistic as it is not influenced by the extreme high and low values that are common in eastern Australia (as it is for river flow). All coastal rainfall sites show maximum rainfall and greatest variability during the summer monsoon from December to March and, despite differences in total rainfall received, the annual distribution of rainfall is similar along the coast[35]. As with SSTs, rainfall anomalies in northeast Queensland tend to vary coherently[29,31,33].

f http://www.aims.gov.au/pages/facilities/weather-stations/weather-index.html

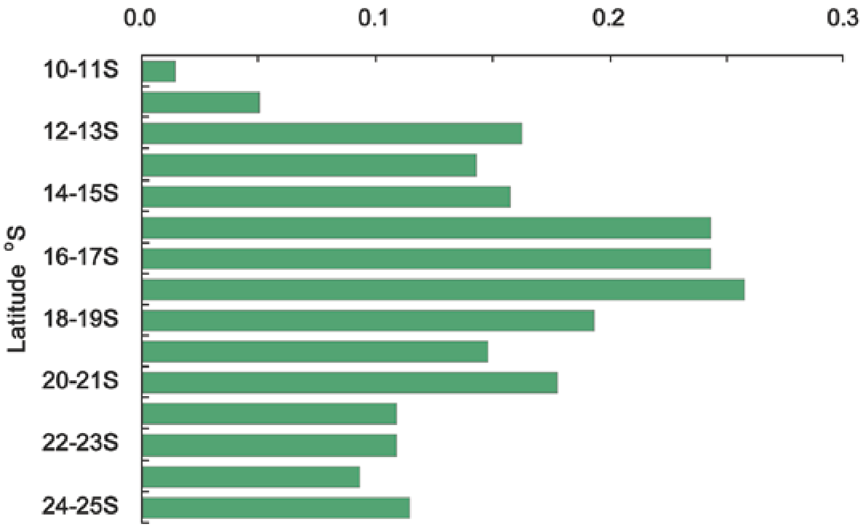
2.3.4 River flow

The highly seasonal and highly variable rainfall regime of northeast Australia also results in highly variable river flows. This extreme variability is characteristic of Australian rivers in comparison to other regions of the world[15,9]. The majority (about 80 percent) of total river flow into GBR coastal waters occurs between 17° S and 23° S with greatest annual flow in March, a month after the rainfall maxima. Over the period 1924 to 2005, median total flow of all rivers entering the GBR was 20 km^3 with a maximum of 94 km^3 in 1974 and minimum of 4 km^3 in 1987[16].

2.3.5 Tropical cyclones

Tropical cyclones during the summer monsoon season are the most spectacular and destructive weather systems affecting the GBR. Conditions suitable for tropical cyclone development occur from November through May. During the period 1969 to 1997, tropical cyclones were observed on the GBR from December through May with highest numbers in January and February[53]. The total number of tropical cyclone days (defined as a day with a tropical cyclone within a given area) along the GBR is highest at 16° S to 18° S and lowest at 10° S to 12° S (Figure 2.5). Tropical cyclones bring destructive winds and waves and heavy rainfall as they cross the GBR and when making landfall can cause elevated sea levels and destructive storm waves (storm surge) as well as high rainfall totals and rapid increases in river flows.

Figure 2.5 *Average number of tropical cyclone days per year for 1° latitudinal bands along the Great Barrier Reef, 1968–1969 to 2002–2003 showing highest activity 15 to 18° S. (Data source: Australian Bureau of Meteorology)*



2.3.6 Inter-annual variability: El Niño-Southern Oscillation

Average surface climate conditions in northeast Australia and the GBR include high inter-annual variability especially for rainfall and river flow. At any given time climatic conditions are likely to differ from these average conditions and are thus termed anomalies. The major source of global short-term climate variability and predictability is the ENSO phenomenon[40]. ENSO events are also the major source of inter-annual climate variability in northeast Australia and along the GBR[32]. ENSO describes the aperiodic variations in the ocean-atmosphere climate of the tropical Pacific, which due to linkages operating through the large-scale atmospheric circulation called teleconnections, causes climate anomalies in many parts of the tropics and extra-tropics[2,40]. ENSO has two phases:

1) El Niño events when the eastern equatorial Pacific is unusually warm, and

2) La Niña events when the eastern equatorial Pacific is unusually cold.

Events typically evolve over 12 to 18 months and, once initiated, their development is to some extent predictable though individual events can develop and decay differently[41]. Distinct climate anomalies occur in northeast Australia and along the GBR with ENSO extremes[32]. During typical El Niño events, the summer monsoon circulation is weaker than normal associated with higher sea level pressure and more south-easterly winds. Cloud amount is reduced with consequent higher radiation and rainfall and river flows are considerably lower than normal (eg for Townsville median rainfall in El Niño years is 779 mm compared to long-term median of 1036 mm). During typical La Niña events, the summer monsoon circulation is stronger than normal with lower sea level pressure and more north-westerly winds. Cloud amount, rainfall and river flows are higher than average (eg for Townsville median rainfall in La Niña years is 1596 mm). Burdekin River flow in El Niño years is 3.8 km^3 compared with 9.2 km^3 in La Niña years. SST anomalies along the GBR are more marked during El Niño than La Niña events[35] (Figure 2.6), with, in particular, warmer than average SSTs occurring during the summer warm season. The differences in the strength of the summer monsoon circulation with ENSO also results in marked differences in the occurrence of tropical cyclones along the GBR with much less activity during El Niño years (Figure 2.7). Overall, the level of disturbance to the GBR appears to be greater during La Niña events when the more vigorous summer monsoon circulation and heightened tropical cyclone activity causes enhanced rainfall and river flow. This is likely to lead to reduced salinity and higher turbidity of GBR waters and increased levels of physical disturbance. Suppression of the summer monsoon and tropical cyclone activity during El Niño events is associated with reduced rainfall and river flow inputs to the GBR and maintenance of more winter-like conditions.

Figure 2.6 *Average monthly sea surface temperature anomalies (°C, from ENSO-neutral) years for 1° latitude bands along the GBR over the 24-month period of 21 El Niño events (left) and 21 La Niña events (right). Filled bars indicate anomalies significantly different from those averaged for ENSO-neutral years at the 5 percent level. Thin black line is average monthly annual cycle. Illustrates the 'typical' GBR SST signals associated with ENSO extremes and their relation to the annual cycle. (Data source: HadISST, 1871 to 2005, Rayner et al.[54])*

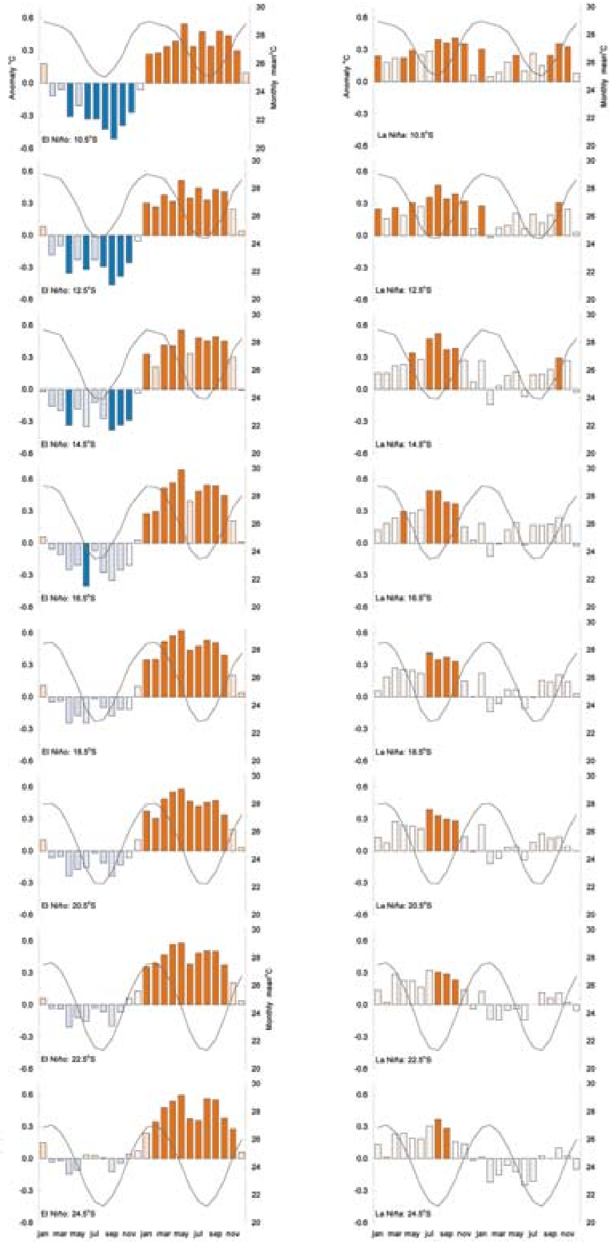
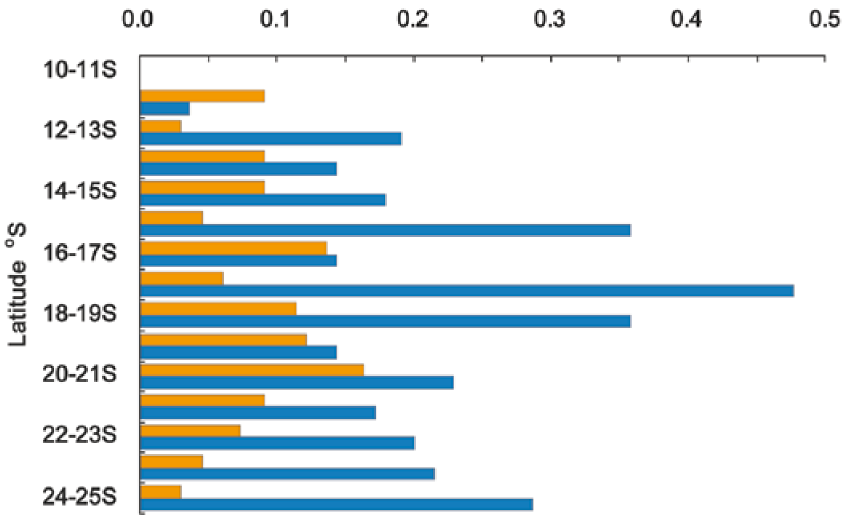


Figure 2.7 *Average number of tropical cyclone days per year for 1° latitudinal bands along the GBR for El Niño (orange, 11 events) and La Niña years (blue, 7 events) during period 1968–1969 to 2002–2003, illustrating the suppressed activity during El Niño events. (Data source: Australian Bureau of Meteorology)*



2.3.7 Decadal variability: Pacific Decadal Oscillation

The strength of the relationship between ENSO extremes and regional climate, including northeast Australia and the GBR, is modulated on decadal timescales by the Pacific Decadal Oscillation (PDO also known as the Inter-decadal Oscillation). This is an El Niño-like pattern of climate variability in the Pacific Ocean[37] that is characterised by persistent warm (1925 to 1946; 1977 to 1998) and cold (1890 to 1924; 1947 to 1976) regimes. Relationships between Australian rainfall and ENSO events are strong, significant and more predictable during PDO cool phases and weak, insignificant and less predictable during PDO warm phases[52].

For northeast Australia, PDO cool regimes are associated with significant correlations between rainfall and indices of ENSO strength (eg Niño 3.4 SST index[g]), greater spatial coherence of rainfall anomalies and greater inter-annual variability of rainfall (ie larger extremes). During PDO warm phases, the opposite conditions prevail with insignificant correlations with ENSO, less spatially coherent rainfall anomalies with reduced inter-annual rainfall variability (Table 2.1). These decadal variations also affect river flow entering the GBR.

g http://www.cpc.noaa.gov/data/indices/

Table 2.1 *Decadal modulation of Queensland October to September rainfall characteristics and ENSO teleconnections by PDO phase*

	PDO phase	Standard Deviation rainfall percent	Correlation rainfall and Niño 3.4 index of ENSO	Percent explained variance by PC1*	Maximum rainfall percent	Minimum rainfall percent
1891 to 1924	Cool	28	-0.60	53	167	31
1925 to 1946	Warm	15	-0.15	35	120	59
1947 to 1976	Cool	33	-0.79	62	196	49
1977 to 1998	Warm	16	-0.11	31	130	77
1891 to 2005		26	-0.54	48	196	31

* PC1 = First Principal Component

2.4 Observed and projected climate

In this Section, observed changes in climate in the vicinity of the GBR are first described for the various climate variables (the Bureau of Meteorology has instrumental records of climate change for Australia[h]). Projections as to how these are likely to change and the level of confidence in such changes with continued climate change are then discussed. These are summarised in Table 2.2 for the years 2020 and 2050 and are based on two IPCC Special Report on Emissions Scenarios (SRES; Appendix 2.1): SRES A2 (most extreme scenario with CO_2 by 2100 three times pre-industrial concentration) and SRES B1 (least extreme scenario with CO_2 by 2100 two times pre-industrial concentration). Various published climate projections for the region are based on a variety of dates into the future[69] (eg 2070). As a general rule of thumb, air temperature changes in tropical and coastal Australia are approximately the same as the average global warming for any given scenario and time into the future[51]. Similarly, L.D.D. Harvey (pers comm 2006) has estimated that summer SST warming in the vicinity of tropical reefs is likely to be 80 to 90 percent of average global change for a given scenario and time into the future. This is higher than suggested by IPCC[23] for annual average tropical SSTs, which tend to be half the global average temperature change.

h http://www.bom.gov.au/silo/products/cli_chg/

Table 2.2 *Projected changes in climate for the Great Barrier Reef region for 2020 and 2050 based on SRES A2 and B1 storylines (see Appendix 2.1)*

	2020		2050	
Projected change	**A2**	**B1**	**A2**	**B1**
Air temperature (relative to 1961 to 1990 average and on basis that tropical and coastal areas of Australia will warm at ~global average[51])	+1.4°C	+0.6°C	+2.6°C	+0.9°C
Air temperature extremes	See Table 2.3 with example for Townsville temperature extremes and warming of 1°C			
SST for GBR (relative to 1961 to 1990 average 25.9°C)	+0.5°C	+0.5°C	+1.2°C	+1.1°C
Rainfall	No consensus on change in average precipitation however 1) intensity of drought associated with given rainfall deficit will be increased due to higher air temperatures 2) intensity of high rainfall events will increase (eg January 1998 Townsville flood event more frequent) 3) more extremes			
Tropical cyclones	No consensus on changes in frequency or spatial occurrence but intensity of tropical cyclones expected to increase, so that although there may not be more tropical cyclones or in new locations but severe tropical cyclones (eg TC Ingrid, TC Larry) likely to be more common (possibility already being muted of a higher category than 5)			
Sea level rise (relative to 1961 to 1990 baseline)	+38cm	+7cm	+68cm	+13cm
Ocean chemistry (estimated decrease in ocean pH based on projections of 0.3 to 0.5 decrease by 2100)	-0.10	-0.06	-0.25	-0.15
ENSO	No consensus on how ENSO frequency and intensity will change but likely to be continued source of aperiodic disturbance in region			
CO_2 parts per million (pre-industrial = 270 ppm)	440	421	559	479

2.4.1 Air temperatures

Observed

Instrumental records since the end of the 19th century show that global temperatures have significantly warmed by about 0.7°C[7,17,24]. Average, maximum and minimum air temperatures over Queensland have significantly warmed since the start of reliable records in the early 20th century (Figure 2.8). The largest changes to date have been observed in minimum temperatures and in winter of approximately 0.9°C (Figure 2.9). These observed changes in average temperatures have been accompanied by changes in daily temperature extremes with more extreme hot days and nights and fewer cold days and nights (Figure 2.10).

Figure 2.8 *Instrumental annual anomalies from 1961 to 1990 mean for a) Queensland maximum air temperatures and b) Queensland minimum air temperatures, 1910 to 2006. Thick line is 10-year Gaussian filter emphasising decadal variability. (Data source: Australian Bureau of Meteorology, Lough[33])*

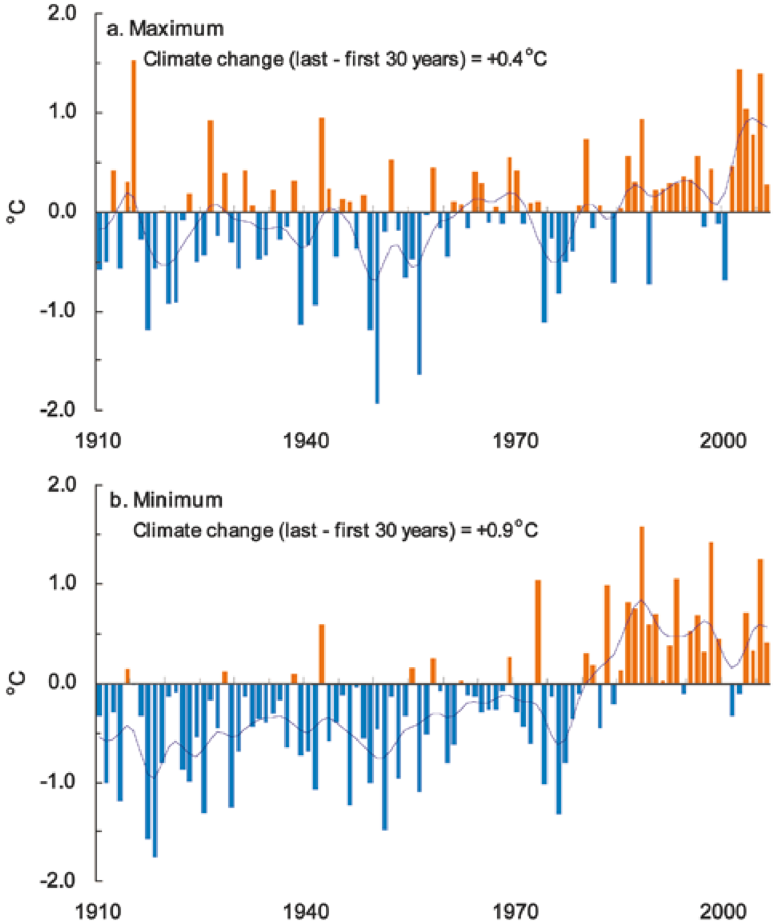


Figure 2.9 *Differences in monthly average (black), maximum (red) and minimum (blue) air temperatures for Queensland, 1977–2006 minus 1910–1939. Filled bars show months where observed changes are significant at the 5 percent level. Illustrates warming has been observed in all months with significant changes most evident for minimum and average air temperatures. (Data source: Australian Bureau of Meteorology, Lough[33])*

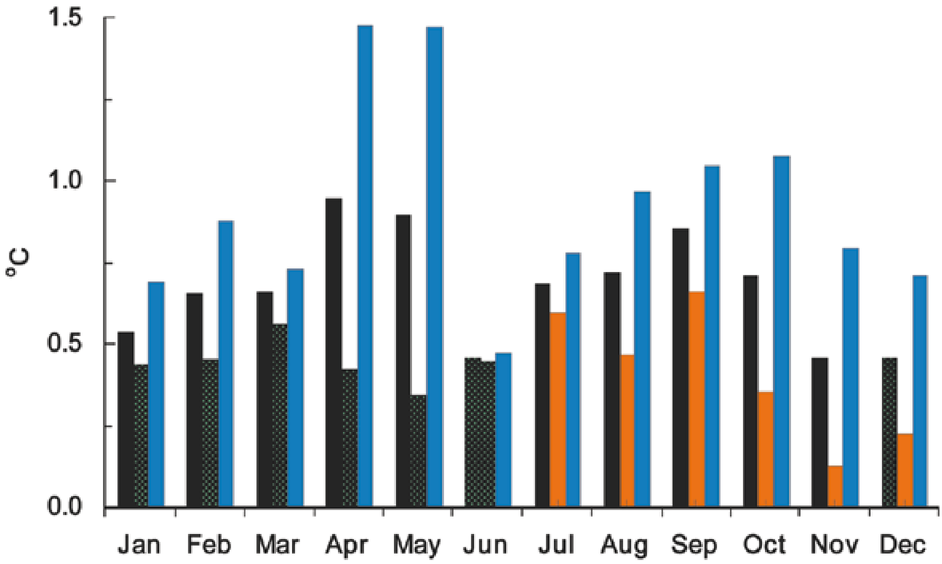
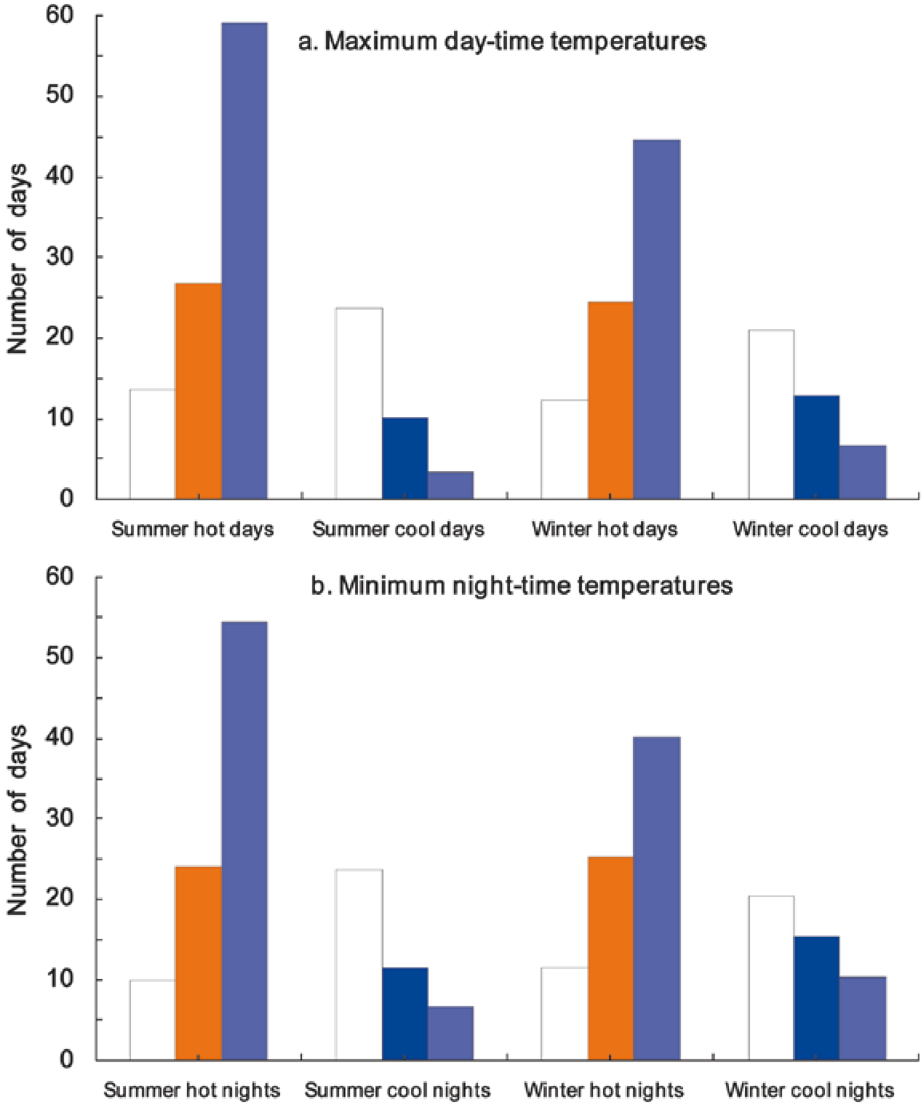


Figure 2.10 *Observed changes in average number of extreme summer and winter a) day-time and b) night-time temperatures for Townsville, Queensland. Based on counts of number of days above 90th percentile (red bars) and below 10th percentile (blue bars) for 1941 to 1960, 1986 to 2005 and projected number with 1°C warming (grey bars). Illustrates already observed increase in extreme hot days and nights and reduction in cool days and nights. (Data source: Australian Bureau of Meteorology)*

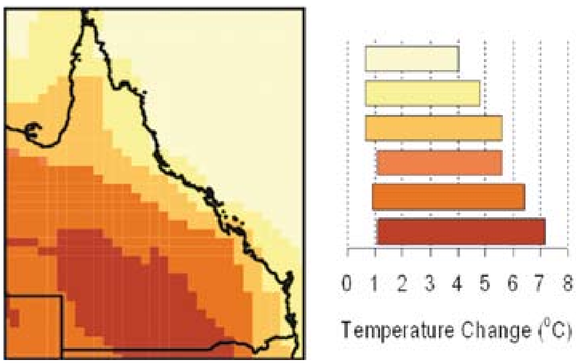


Projected

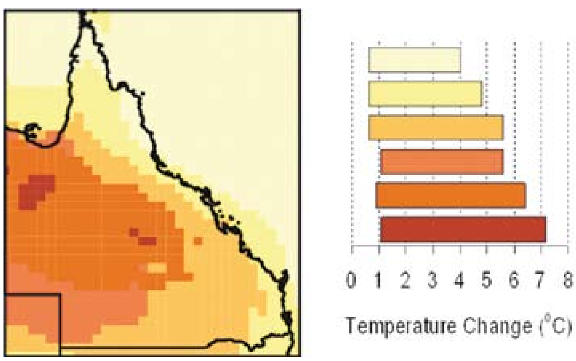
There is good agreement between different climate models as to the direction and magnitude of continued warming in northeast Australia. Regional models suggest slightly lower warming along the Queensland coastal strip compared to interior Queensland[65,69,21] (Figure 2.11a and b). Coastal air temperatures are projected to increase (above 1990 levels) by as much as 4 to 5°C by 2070[69] (Table 2.2 for 2020 and 2050). This projected warming will increase the frequency of occurrence of warm temperature extremes and decrease the number of cold temperature extremes (Table 2.3 gives examples of changes in maximum daytime and minimum night time temperature extremes for Townsville with 1°C global warming[21]).

Certainty:	
High, statistically significant warming already observed and projected to continue	
Regional projection:	
Greater warming inland than along coastal strip	

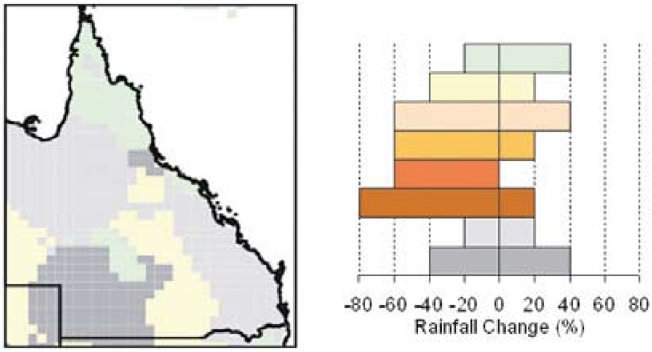
Figure 2.11 *Regionally based seasonal temperature and rainfall projections for Queensland to 2070. Horizontal bars indicate the ranges from several different climate models (Source: Whetton et al.[69])*



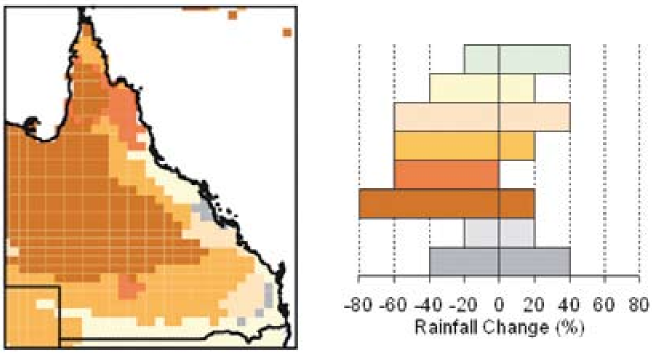
a. Summer temperature



b. Winter temperature



c. Summer rainfall



c. Winter rainfall

Table 2.3 *Example of changes in air temperature extremes for Townsville associated with a 1°C warming (ie by 2020 for A2 and by 2050 for B1 scenarios)*[i]

Warm extremes	Summer number of days above 33°C	Winter number of days above 30°C	Summer number of nights above 26°C	Winter number of nights above 21°C
1961 to 1990	16	15	18	20
+1°C warming	59	45	55	40
Cold extremes	Summer number of days below 28°C	Winter number of days below 24°C	Summer number of nights below 20°C	Winter number of nights below 11°C
1961 to 1990	16	19	20	17
+1°C warming	3	7	7	10

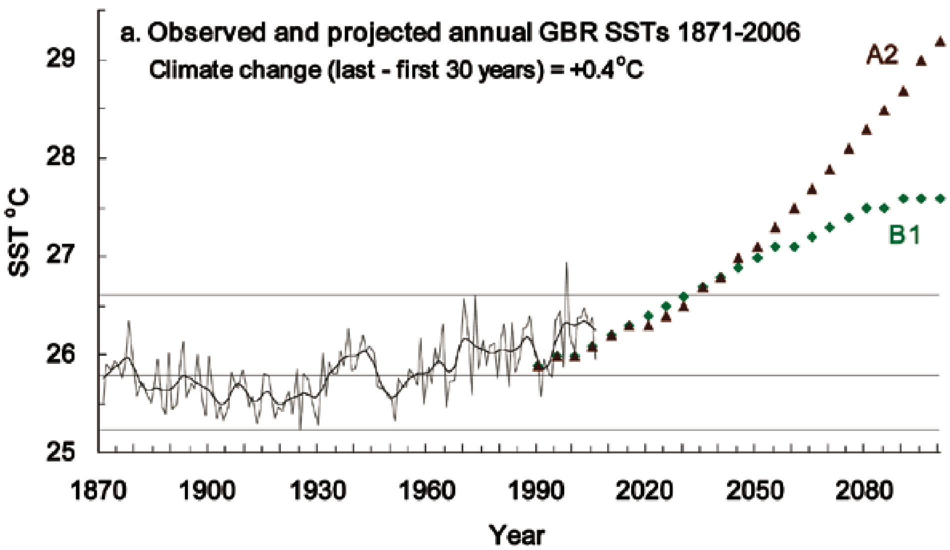
i Based on 90th and 10th percentiles of daily maximum and minimum temperatures at Townsville Bureau of Meteorology station

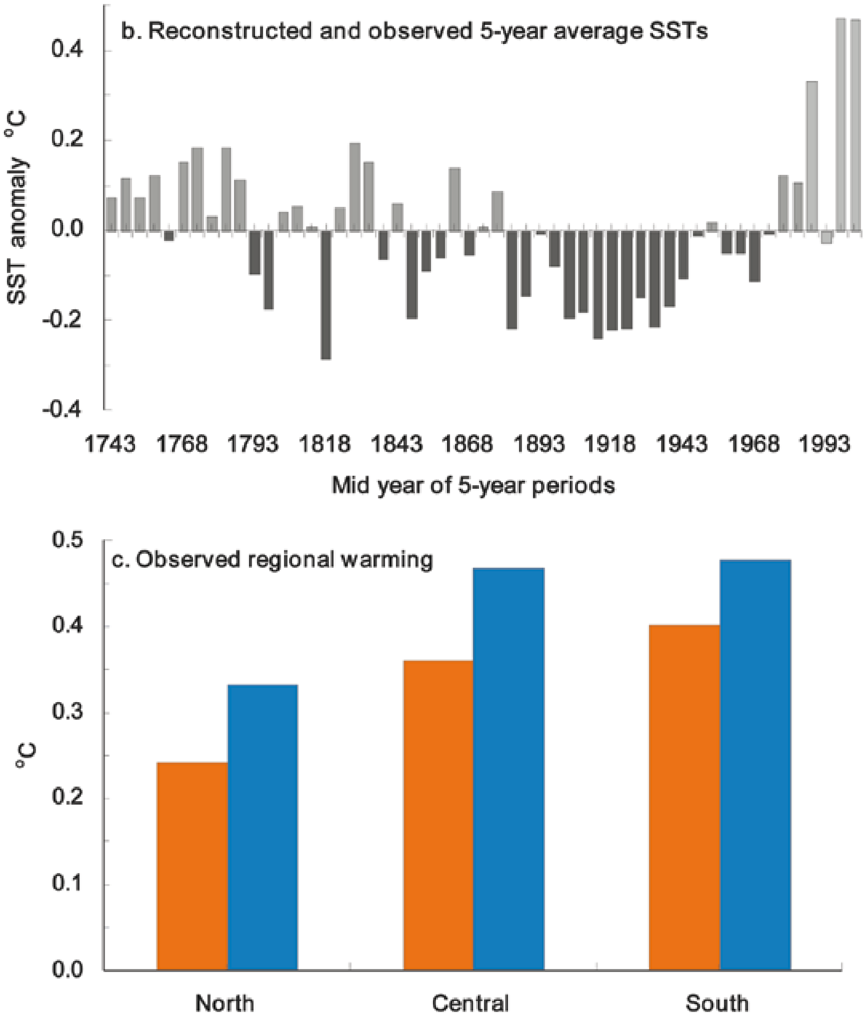
2.4.2 Sea surface temperatures

Observed

Globally, SSTs have warmed significantly as global climate has warmed over the past century[23]. There is also recent evidence that this warming is not just occurring at the surface and that the heat content of the global oceans has increased since 1960[4]. Average SSTs of the GBR have significantly warmed since the end of the 19th century with average temperatures for the most recent 30 years (1976 to 2005) 0.4°C warmer than the earliest instrumental 30 years (1871 to 1900; Figure 2.12a). Combining reconstructions from coral records and the recent instrumental record suggests that SSTs in the GBR are now warmer than they have been since at least back to the mid-17th century[36]. Figure 2.12b shows reconstructed SST from Sr/Ca ratios measured in up to seven coral cores from the central GBR by Hendy et al.[20] who note 'SSTs for the 18th and 19th centuries that are as warm as, or warmer than the 20th century'. The observed warming of the GBR has also been greater in winter than in summer and greater in the central and southern GBR than in the northern GBR (Figure 2.12c).

Figure 2.12 *a) Observed (1871 to 2006) and projected (to 2100 for SRES A2 and B1 scenarios) annual sea surface temperatures for the GBR. Thick black line is 10-year Gaussian filter emphasising decadal variability; central black line is observed average annual SST, 1871 to 1989 (25.8 oC) and grey lines indicate observed maximum and minimum values. (Data sources: HadISST, NOAA OI.v2 SST and ReefClim, Roger Jones, CSIRO). b) Reconstructed (1741 to 1985) and observed (1985 to 2005) average 5-year sea surface temperature anomalies (from long-term average) for the GBR. This coral series ends in 1985. c) Observed warming (1977 to 2006) minus (1871 to 1900) summer (red) and winter (blue) sea surface temperatures in the north, central and southern GBR. All differences significant at the 5 percent level. Greatest warming observed in winter and in central and southern GBR*





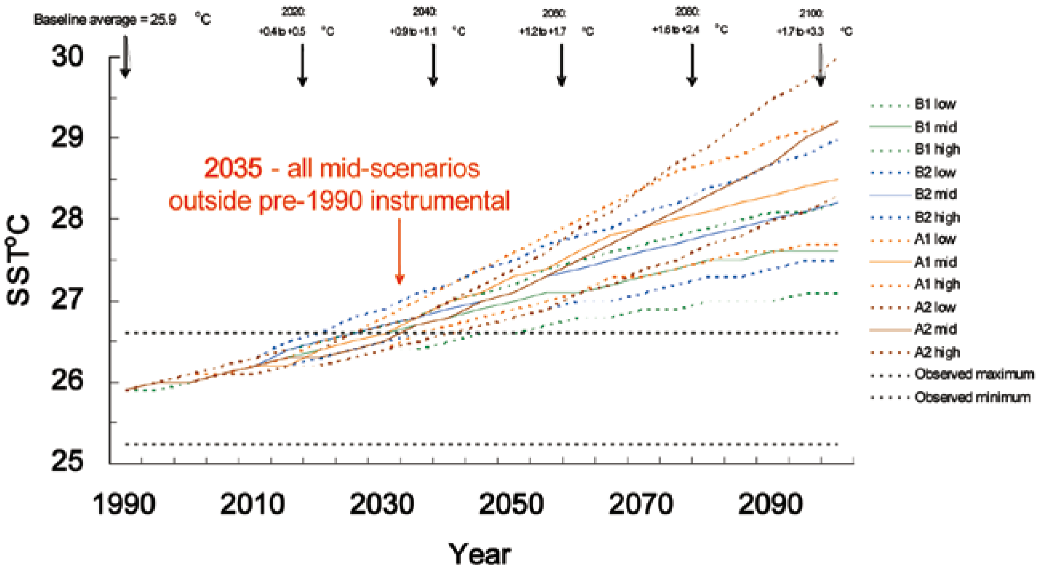
Projected

Average annual SSTs on the GBR are projected to continue to warm over the coming century and could be between 1 and 3°C warmer than present temperatures by 2100 (Figure 2.13). Whatever climate scenario is used, all projections are outside the observed GBR SST climate range up to 1990 by the year 2035. However, these scenarios do not show any differences in projected warming with either latitude or season. This does not mean that there will not be such spatial and seasonal changes and, based on observed trends, it is likely that SSTs might warm more in winter and in the southern GBR. Projected average SSTs by 2020 could be 0.5°C warmer and greater than 1°C warmer by 2050 (Table 2.2). There is no indication in current climate projections as to how SST extremes will change but it is likely that they will follow a similar path as air temperatures extremes (see Townsville example in Table 2.3) with a shift towards more warm SST extremes and reduction in cold SST extremes.

Certainty:
High, statistically significant warming already observed and projected to continue

Regional projection:
Greater warming in southern GBR and in winter

Figure 2.13 *Range of GBR annual sea surface temperature projections through 2100 for various SRES scenarios and climate sensitivities. (Data source: ReefClim, Roger Jones, CSIRO)*

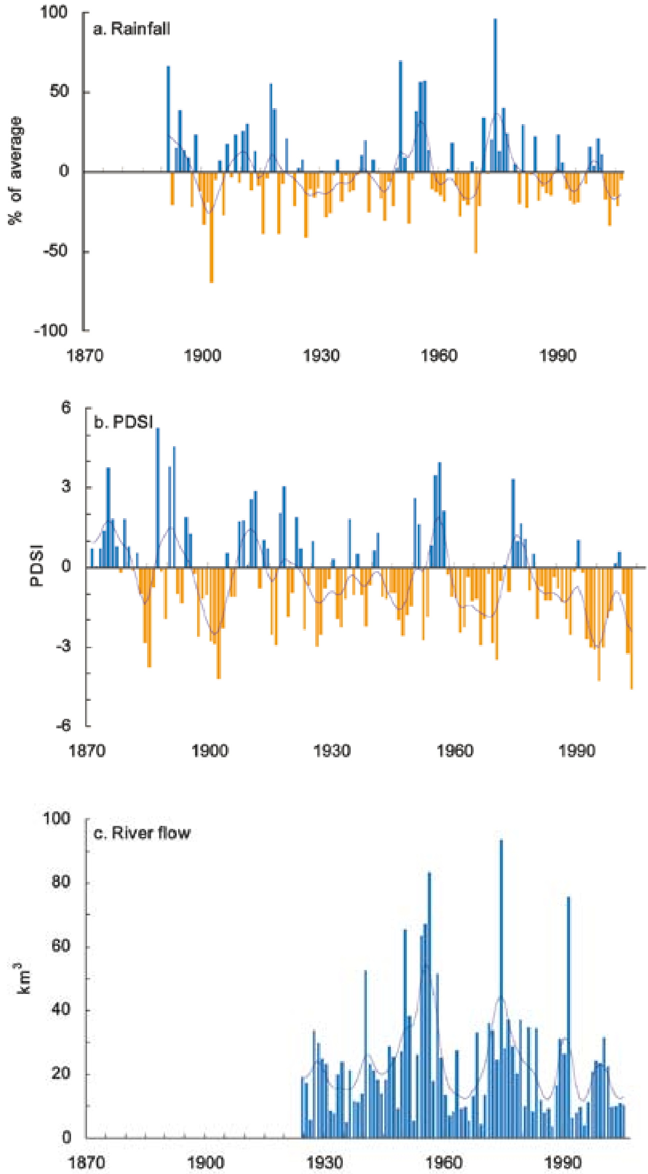


2.4.3 Rainfall and river flow

Observed

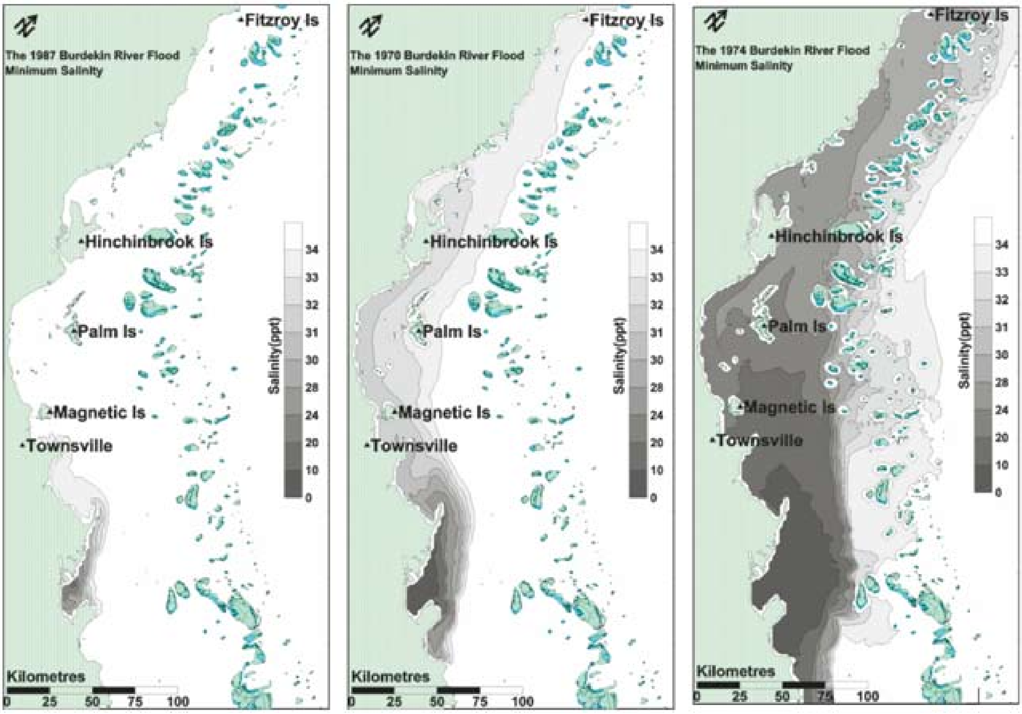
Observed variations of Queensland rainfall (Figure 2.14a) over the past century show high inter-annual and decadal variability with 1902 (culmination of the federation drought), the driest year on record, and 1974 the wettest. The 1950s and 1970s were characterised by above average rainfall. Calculation of a linear trend from the 1950s indicates decreasing rainfall over northeast Australia but this is due to the wetter conditions of this decade and there is no overall trend towards wetter or drier conditions. Warmer air temperatures have, however, increased the intensity of observed drought conditions for a given rainfall deficit[48,11] (Figure 2.14b). High inter-annual and decadal variability (similar to rainfall) also characterises freshwater inputs to the GBR[16] (Figure 2.14c) but, again, there is no long-term trend in the amount of freshwater entering the GBR lagoon. The spatial extent of freshwater associated with seasonal flood plumes modelled by King et al.[27] illustrates the range of extremes in minimum salinity affecting tropical marine ecosystems (Figure 2.15).

Figure 2.14 *a) Queensland October-September rainfall index, 1891 to 2006, as percent anomaly from long-term mean; b) East tropical Queensland October-September Palmer Drought Severity Index (which uses both rainfall and temperature), 1871 to 2003; and c) All-river October-September flow into GBR lagoon. Thick line is 10-year Gaussian filter emphasising decadal variability. Only the PDSI shows a significant downward trend towards more intense droughts. (Data sources: Australian Bureau of Meteorology, Lough[29j], Dai et al.[11], Furnas[16])*



j http://www.cdc.noaa.gov/cdc/data.pdsi.html

Figure 2.15 *Modelled minimum salinity for the GBR for a) 1987 representing a dry year; b) 1970 representing an average year; and c) 1974 representing the wettest year on record. (Data source: King et al.[27])*



Projected

General global projections for a warmer world are for an enhanced hydrological cycle with more extreme droughts and floods and enhanced evaporation[23,24]. Regional projections for changes in average rainfall in northeast Queensland are, however, less clear. This is due, in part, to the poor ability of current climate models to correctly simulate the Australian summer monsoon[45], and the resulting uncertainty amongst different climate models about the direction and magnitude of change[69,21] (Figure 2.11c and d). Interpretation of regional changes is also confounded by the high natural inter-annual variability of regional rainfall and river flow and, again, the uncertainty introduced into projections by lack of knowledge as to how ENSO events might change in a warmer world. As already observed, however, it is likely that a given rainfall deficit in a warmer world will result in greater drought conditions than the same rainfall deficit in the early 20th century. This is due to higher temperatures increasing evaporative losses, decreasing soil moisture and, thus, the intensity of drought conditions and reduced river flows[65]. Most climate models project increases in extreme daily rainfall events – even where projected changes in average rainfall are small or unclear[65]. The intensity of extreme rainfall events such as the January 1998 Townsville flood event might become more common.

In the absence of clear projections as to changes in average rainfall and river flow, it can be assumed that inter-annual and decadal variability of northeast Australian rainfall and river flow (and modulation by ENSO and PDO) will continue in a warmer world[64]. The magnitude of droughts and high intensity rainfall events are likely to be greater in a warmer world compared to current climate conditions, with consequent effects on river flow and the spatial extent of flood plumes affecting the GBR. Thus, the observed extremes of very low flow years and very high flow years (Figure 2.15 left and right) are likely to be more common.

Certainty:
Low for regional changes in average rainfall and river flow but extremes likely to be greater

Regional projection:
Similar spatial and inter-annual variability modulated by ENSO and PDO

2.4.4 Tropical cyclones

Observed

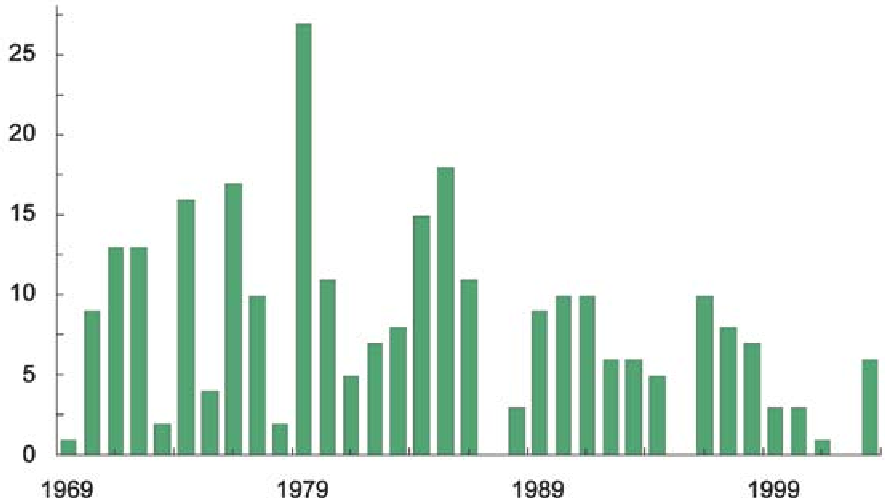
There is mounting observational evidence that the destructive potential of tropical cyclones around the world has increased in recent decades[14,68]. For the Australian region, there is evidence from the period 1970 to 1997 that despite a decrease in the number of tropical cyclones, there was an increase in the number of intense cyclones[49]. Puotinen et al.[53] provide the most detailed description of the occurrence and intensity of tropical cyclones affecting the GBR over the period 1969 to 1997. Over this period, there were no category 5 and only two category 4 tropical cyclones (The Australian Bureau of Meteorology uses a 5-point scale for categorising the intensity of tropical cyclones. The most severe, category 5, has maximum wind gusts greater than 279 km per hour, average wind speeds greater than 200 km per hour and central pressures less than 930 hectoPascal. This category is equivalent to categories 4 to 5 on the Saffir-Simpson scale used in the United Statesk). Although there has been an apparent decline in the number of tropical cyclone days affecting the GBR (Figure 2.16), Tropical Cyclone Ingrid (category 4) and Tropical Cyclone Larry (category 5) occurred in 2005 and 2006, respectively. This possible increase in severe tropical cyclones is consistent with the suggestion of Nicolls et al.[49] that although the number of tropical cyclones may have declined, the intensity of those that occur is greater.

Projected

Although warmer water temperatures might be expected to increase the intensity of tropical cyclones, their formation depends upon a number of other factors[60]. It is, however, likely that tropical cyclones in a warming world will be more intense with higher maximum wind speeds and greater rainfall[24]. Although there are no clear indications that the number and preferred locations of tropical cyclones will change in the Australian region, there is some evidence that their intensity will increase as measured, for example, by higher maximum wind speeds[65,66]. More intense tropical cyclones will also interact with higher sea levels to produce more devastating storm surges and coastal inundation

k http://www.bom.gov.au/weather/wa/cyclone/about/faq/faq_def_2.shtml

Figure 2.16 *Annual number of tropical cyclone days within the GBR, 1969 to 2003 (Data source: Australian Bureau of Meteorology)*



in a warmer world[39]. As an example of what this might mean, category 3 Tropical Cyclone Althea, which affected Townsville in December 1971, was associated with a storm surge of 3.7 metres above normal tide but occurred during a low tide, thus minimising the effects. With rising sea level, a 3.7 metre storm surge could become a 3.8 to 8.7 metre storm surge by 2100 that, if added to a typical high tide in Townsville (4.1 metres on 9 February 2005), would result in a local sea level surge of 7.9 to 12.8 metres.

It can be assumed, therefore, that tropical cyclones will continue to exert an aperiodic influence on the GBR with a similar spatial and seasonal distribution in occurrence as present. Inter-annual variations in tropical cyclone activity are also likely to continue to be modulated by ENSO events with more activity during La Niña and less during El Niño years. Changes in ENSO extremes in a warmer world will also affect tropical cyclone occurrence, frequency, and associated impacts on the GBR. The intensity of tropical cyclones may however, increase with severe tropical cyclones such as Tropical Cyclone Ingrid (March 2005) and Tropical Cyclone Larry (March 2006) being more characteristic of the future climate than the recent past.

Certainty:
Moderate to high that the intensity of tropical cyclones will increase but low as to whether there will be changes in location and frequency

Regional projection:
Similar spatial distribution – modulated by ENSO

2.4.5 Sea level

Observed

As global climate warms, sea level rises due to thermal expansion of the oceans and the contribution of additional water through the melting of mountain glaciers and continental ice sheets. As a result, sea level appears to be rising at a rate of 1 to 2 mm per year. A recent reconstruction of global mean sea level from 1870[10] indicates that between January 1870 and December 2004, global sea level rose by 195 mm. The authors also found observational evidence (matching climate model simulations) of a significant acceleration in the rate of global sea level rise of 0.13 ± 0.006 mm per year. The observed trend in sea level for Cape Ferguson, near Townsville, from September 1991 through May 2006 is 2.9 mm per year[47].

Projected

If the observed acceleration in sea level rise[10] continues to 2100, then global sea level would be 310 ± 30 mm higher than in 1990. This corresponds to the middle of the IPCC[23] projected range of sea level rise of 100 to 900 mm and a narrower range of 180 to 590 mm of the IPCC[24] by 2100. These ranges may however, be higher as the Greenland ice sheet appears to be melting faster than expected[12,63]. There will also be regional variations in the magnitude of sea level rise due to local tectonic changes (though these are minimal in Australia), ocean circulation patterns and inter-annual variability modulated, for example, by ENSO events. How much land inundation occurs for a given sea level rise depends on coastal characteristics. For example, a 1 metre sea level rise will be associated with a 100 metre recession for a sandy beach. Continued sea level rise is a certainty and even if greenhouse gas emissions were halted at 2000 levels, sea level would continue to rise at about 10 cm per century due to thermal inertia of the climate system[43,70], and 'substantial long-term change may be impossible to avoid'.

Certainty:
High that sea level has and will continue to rise and the rate may accelerate

Regional projection:
Limited, regional up to 0.68 metre increase by 2050, global 0.1 to 0.9 metre increase by 2100

2.4.6 Ocean chemistry

Observed

The oceans absorb carbon dioxide (CO_2) from the atmosphere and are estimated to have absorbed about half of the excess CO_2 released into the atmosphere by human activities in the past 200 years. About half of this anthropogenic CO_2 is in the upper 10 percent of oceans (less than 1000 metres depth) due to slow ocean mixing processes. This absorbed CO_2 is resulting in chemical changes in the ocean, which it is estimated has already caused a decrease in oceanic pH of 0.1[55,28]. This is referred to as ocean acidification as the oceans are becoming more acidic, though they are still alkaline.

Projected

With continued emissions of CO_2, oceanic pH is projected to decrease by about 0.4 to 0.5 units by 2100 (a change from 8.2 to 7.8 associated with a surface water decrease in CO_{3-} by 47 percent of pre-industrial levels). This is outside the range of natural variability and a level of ocean acidity not experienced for several hundreds of thousands of years. Of particular concern is that the rate of this change in ocean chemistry is about 100 times faster than at any other time over the past several million years. In addition 'ocean acidification is essentially irreversible during our lifetimes'[55,62,28] and would take tens of thousands of years to return to pre-industrial levels. The magnitude of projected changes in ocean chemistry can be estimated with a high level of confidence but the impacts on marine organisms and various geochemical processes are much less certain. The scale of changes may also vary regionally with the Southern Ocean most likely seeing the greatest changes in the short term. In addition, changes in ocean chemistry will result in interactions and feedbacks with the global carbon cycle, atmospheric chemistry and global climate – in ways that are currently not understood.

Increased CO_2 lowers oceanic pH, increases the amount of dissolved CO_2, reduces the concentration of carbonate ions and increases the concentration of bicarbonate ions. All of these changes will affect marine organisms and processes. Many marine organisms depend on current ocean chemistry to calcify, ie make shells, plates and skeletons. Calcification rates of several major groups of marine calcifying organisms, from both neritic and pelagic environments, will very likely decrease in response to changes in ocean carbonate chemistry. As well as corals, major groups of planktonic calcifiers likely to be affected include coccolithophora and foraminifera (calcite) and pteropods (aragonite).

Given the levels of uncertainties (primarily in terms of organism responses and interactions with other climate change variables), it is assumed that the ability of marine calcifying organisms (such as corals) to produce their skeletons will gradually decline over the 21st century, resulting in weaker and less robust skeletons (Hoegh-Guldberg et al. chapter 10). There is, however, little detailed information about high-resolution spatial patterns (eg cross-shelf) of change in ocean chemistry for the GBR. Recent studies demonstrate that the distribution of anthropogenic CO_2 in the oceans is not uniform[56]. As of 1995, aragonite saturation levels were considered optimal in the far northern GBR and adequate in the south. By 2040 the whole GBR will be marginal for coral reefs and, by 2100, the GBR will have low to extremely low aragonite saturation[28].

Certainty:
High that oceans have become and will be more acidic

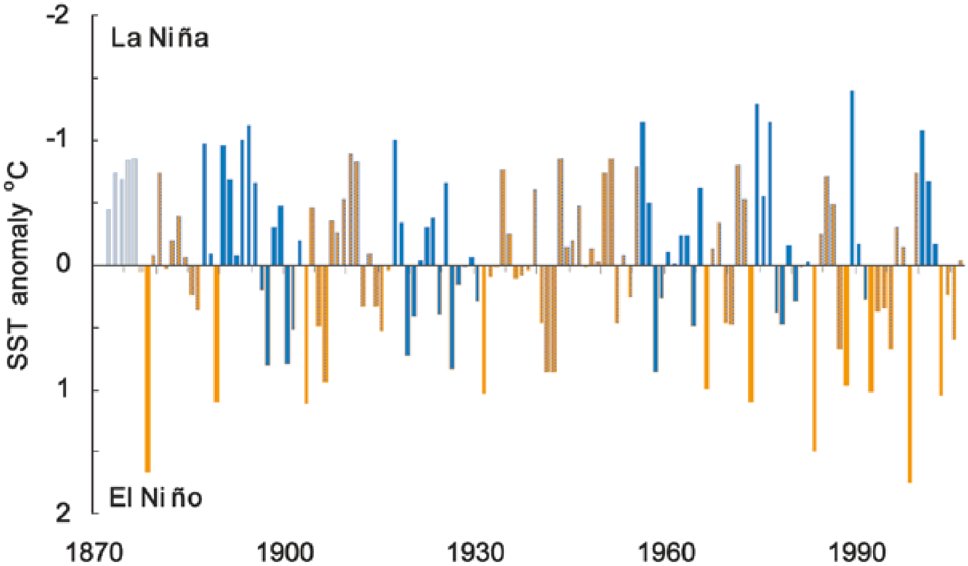
Regional projection:
Limited, generic 0.5 drop in pH by 2100

2.4.7 El-Niño Southern Oscillation

Observed

ENSO events (both El Niño and La Niña) are a significant source of inter-annual surface climate variability in northeast Queensland and the GBR. The instrumental ENSO record dating back to the late 19th century shows repeated occurrence of ENSO extremes. However there is no obvious trend toward more frequent El Niño or La Niña conditions (Figure 2.17). The 1997 to 1998 El Niño event is considered to be the strongest on record[40] and there is considerable debate as to whether this is evidence of changes in ENSO frequency and intensity that might be linked with climate change.

Figure 2.17 *Niño 3.4 May/April average sea surface temperature index of ENSO activity, 1872 to 2006 (axis inverted). Large positive values characterise El Niño events and large negative values characterise La Niña events. Most extreme (± 1 standard deviation) shown by filled bars. (Data source: HadISST, NOAA/NWS/NCEP Climate Diagnostics Bulletin[I])*



Projected

Although seasonal climate predictions of ENSO events are now reasonably reliable[40], projections of how ENSO will change with continued climate change are still unclear[23]. ENSO is the largest source of inter-annual climate variability in the instrumental climate record yet the relationship between ENSO and global warming is largely unknown. It is unclear whether enhanced greenhouse conditions will favour more El Niño or more La Niña-like conditions and/or changes in intensity and frequency of ENSO extremes[67]. This uncertainty also contributes to regional uncertainties as to how northeast Australia and GBR rainfall, river flow and tropical cyclones will change as climate change continues.

I http://www.cpc.noaa.gov/products/analysis_monitoring/bulletin/

In the absence of clear projections as to whether the occurrence, intensity and frequency of El Niño or La Niña events might change over the coming decades and century, it is assumed that ENSO events will continue to be a source of climate variability for this region and that this will be modulated by the Pacific Decadal Oscillation.

Certainty:
Low as to how ENSO frequency and intensity will change

Regional projection:
Likely to continue as a source of high inter-annual climate variability in northeast Australia and GBR region

2.4.8 Ultraviolet radiation

The stratospheric ozone layer protects life on Earth from the harmful effects of ultraviolet B (UVB) radiation. Human use of chlorine and bromine containing gases reduced the effectiveness of this layer leading to depletion of the ozone layer and the seasonal appearance of ozone holes over polar regions. Australia is particularly vulnerable given its close proximity to the Antarctic ozone hole. Although the Montreal Protocol (signed in 1987) has taken steps to stop ozone depletion, full recovery of the protective stratospheric ozone layer is not expected until at least 2020[25]. In addition, there may be an interactive effect with climate change as one of the consequences of global warming is a cooler stratosphere, which leads to further depletion of the ozone layer, just as it should be recovering. This is because a cooler stratosphere allows polar stratospheric clouds (which provide the necessary surface area for chlorine compounds to actively contribute to ozone loss) to form earlier and persist longer than usual. It, therefore, seems likely that harmful UVB levels may continue to increase with climate change[m]. Ultraviolet radiation receipt in tropical northern Australia is already extremely high due to its location close to the equator. A decrease in column ozone is associated with increased ultraviolet radiation. Such changes are, however, primarily limited to mid-latitude and polar regions with no significant trends observed in tropical regions[72]. Changes in ultraviolet radiation are not therefore, projected in the GBR region.

2.5 Non-linear and catastrophic changes

There are several potential non-linear and catastrophic changes that could occur as global climate continues to rapidly change ('climate surprises' and possible 'runaway greenhouse'). These potential 'wild cards'[13] include: a slowing or shutdown of the North Atlantic thermohaline circulation; more rapid sea level rise (order of several metres) due to disintegration of the Greenland and/or West Antarctic ice sheets; and the initiation of a runaway greenhouse effect as unanticipated feedbacks in the global climate system result in more rapid warming. Terrestrial carbon sinks are, for example, currently absorbing significant amounts of excess atmospheric carbon dioxide. If these sinks weaken or collapse, the Earth's climate system could be shifted to a new state of persistently higher greenhouse gas concentrations and higher mean temperatures[58]. These large-scale abrupt changes

m http://www.ess-home.com/news/global-warming/ozone-depletion.asp

can be defined as 'dangerous climate change'. If such catastrophic changes occur, the consequences for the global community and ecosystems would be so great as to render any consideration of localised impacts trivial.

For northeast Queensland and the GBR, significant consequences would be expected from abrupt, unanticipated shifts in a) ENSO behaviour and b) Asian monsoon system. A significant shift towards more El Niño-like conditions would create significant problems for eastern Australia and be considered dangerous climate change[58].

2.6 Summary

The large-scale Australian summer monsoon and south-east trade wind circulations dominate the sub-tropical to tropical surface climate of northeast Australia and the GBR. The highly seasonal and highly variable inter-annual rainfall, river flows and occurrence of tropical cyclones are significantly modulated by global-scale ENSO events. These are in turn, modulated on decadal timescales by the Pacific Decadal Oscillation. Sea surface temperatures, air temperatures, rainfall and river flow tend to vary coherently across the region.

Surface climate is already showing evidence of significant changes due to the enhanced greenhouse effect with air and sea surface temperatures now significantly warmer than during the 19th and 20th centuries. The highly variable rainfall and river flow regimes do not currently show any evidence of significant changes towards either wetter or drier conditions. Although there appears to be a recent downward trend in the level of tropical cyclone frequency affecting the region, there is some indication of an increase in more intense tropical cyclones. Sea level is gradually rising.

Land and sea surface temperatures are projected to continue to warm and sea level is projected to continue to rise during the 21st century. These projections have a high degree of certainty. Globally, ocean chemistry has become more acidic and this is expected to increase during the 21st century. Key uncertainties exist in projecting what changes may occur to the highly variable rainfall and river flow regimes of the region. It is, however, highly likely that extreme dry years will be more extreme, due to higher temperatures, and that the intensity of individual rainfall events will increase, ie the rainfall and river flow regimes will become even more extreme than in the recent past. The intensity of tropical cyclones is likely to increase although there are no clear indications of changes in their occurrence and location. Another source of uncertainty relates to how ENSO events will change as the world continues to warm (Table 2.4). Changes in the frequency and intensity of extreme events (eg tropical cyclones, extreme rainfall and river flood events) and the rates of temperature changes are likely to be of critical ecological importance in the region as climate continues to change (chapters 5 to 22).

Table 2.4 *Summary of certainty and regional detail of projected changes*

Variable	Certainty	Regional projection
Air temperature rise	High, already observed	Greater inland than along coast
SST rise	High, already observed	Greater in southern GBR and in winter
Rainfall and river flow	Low for changes in averages High for more extremes	Similar spatial and inter-annual variability modulated by ENSO and PDO
Tropical cyclones	Low for location and frequency High for increased intensity	Similar distribution but modulated by ENSO
Sea level rise	High, already observed and may accelerate	Limited, generic 0.1 to 0.9 m by 2100
Ocean acidification	High, already observed drop in pH	Limited, generic 0.5 pH drop by 2100
ENSO events	Low	Continued source of high inter-annual variability but modulated by PDO

References

1 Allan RB and Pariwono JI (1990) Ocean-atmosphere interactions in low-latitude Australia. *International Journal of Climatology* 10, 145–178.

2 Allan R, Lindesay J and Parker D (1996) *El Niño southern oscillation and climatic variability.* CSIRO Publishing, Victoria.

3 Arrhenius S (1896) On the influence of carbonic acid in the air upon the temperature of the ground. *Philosophical Magazine* 41, 237–276.

4 Barnett TP, Pierce DW, AchutaRao KM, Glecker PJ, Santer BD, Gregory JM and Washington WM (2005) Penetration of human-induced warming into the world's oceans. *Science* 309, 284–287.

5 Bradley RS (1999) *Paleoclimatology. Reconstructing climates of the quaternary.* Academic Press, San Diego.

6 Bradshaw WE and Holzapfel CM (2006) Evolutionary response to rapid climate change. *Science* 312, 1477–1478.

7 Brohan P, Kennedy JJ, Harris I, Tett SFB and Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new data set from 1850. *Journal of Geophysical Research* 111, D12106, doi: 10.1029/2005JD006548.

8 Callendar GS (1938) The artificial production of carbon dioxide and its influence on temperature. *Quarterly Journal Royal Meteorological Society* 64, 223–237.

9 Chiew FHS and McMahon TA (1993) Detection of trend or change in annual flow of Australian rivers. *International Journal of Climatology* 13, 643–653.

10 Church JA and White NJ (2006) A 20th century acceleration in global sea level rise. *Geophysical Research Letters* 33, L01602, doi:10.1029/2005GL024826.

11 Dai A, Trenberth KE and Qian T (2004) A global dataset of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. *Journal Hydrometeorology* 5, 1117–1130.

12 Dowdeswell JA (2006) The Greenland ice sheet and global sea level rise. Science 311, 963–964.

13 Dupont A and Pearman G (2006) Heating up the planet. Climate change and security. *Lowy Institute Paper 12*, Lowy Institute for International Policy, NSW, Australia.

14 Emanuel K (2005) Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436, doi:10.1038/nature03906.

15 Finlayson BL and McMahon TA (1988) Australia v. the world: a comparative analysis of streamflow characteristics. In: RF Warner (ed) *Fluvial Geomorphology of Australia*. Academic Press, Sydney, pp. 17–40.

16 Furnas MJ (2003) *Catchments and Corals: Terrestrial Runoff to the Great Barrier Reef.* Australian Institute of Marine Science and Reef CRC, Townsville.

17 Hansen J, Sato M, Ruedy R, Lo K, Lea DW and Medina-Elizade M (2006) Global temperature change. *Proceedings of the National Academy of Sciences* 103, 14288–14293.

18 Hendon HH and Liebmann B (1990) A composite study of onset of the Australian summer monsoon. *Journal Atmospheric Science* 47, 2227–2240.

19 Hendon HH, Davidson NE and Gunn B (1989) Australian summer monsoon onset during AMEX, 1987. *Monthly Weather Review* 117, 370–390.

20 Hendy EJ, Gagan MK, Alibert CA, McCulloch MT, Lough JM and Isdale PJ (2002) Abrupt decrease in tropical Pacific sea surface salinity marks end of Little Ice Age. *Science* 295, 1511–1514.

21 Hennessy K, Macadam I and Whetton P (2006) *Climate change scenarios for initial assessment of risk in accordance with risk management guidance*. Prepared for the Australian Greenhouse Office, Department of the Environment and Heritage, CSIRO Marine and Atmospheric Research, Aspendale, Australia.

22 Hickling R, Roy DB, Hill JK, Fox R and Thomas CD (2006) The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology* 12, 450–455.

23 IPCC (Intergovernmental Panel on climate Change) (2001) Climate Change 2001. The Scientific Basis. In: JT Houghton, Y Ding, DJ Griggs, N Noguer, PJ van der Linden, X Dai, K Maskell, and CA Johnson (eds) *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge United Kingdom and New York, NY, USA.

24 IPCC SPM (2007) *Climate Change 2007: The Physical Science Basis.* Summary for Policymakers. IPCC Secretariat, http://www.ipcc.ch.

25 IPCC/TEAP (2005) *Safeguarding the ozone layer and the global climate system: issues related to hydrofluorocarbons and perfluorocarbons.* Summary for Policymakers and Technical Summary (http://arch.rivm.nl/env/int/ipcc/pages_media/SROC-final/srocspmts_en.pdf).

26 Jones RN (2000) Managing uncertainty in climate change projections – issues for impact assessment. *Climatic Change* 45, 403–419.

27 King BM, McAllister F, Wolanski E, Done T and Spagnol S (2001) River plume dynamics in the central Great Barrier Reef. In: E Wolanski (ed.) *Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef*. CRC Press, Boca Raton, pp. 145–159.

28 Kleypas JA, Feely RA, Fabry VJ, Langdon C, Sabine CL and Robbins LL (2006) *Impacts of Ocean Acidification on Coral Reefs and other marine calcifiers: A Guide for Future Research*, Report of a workshop held 18-20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the US Geological Survey.

29 Lough JM (1991) Rainfall variations in Queensland, Australia: 1891 to 1986. *International Journal of Climatology* 11, 745–768.

30 Lough JM (1992) Variations of sea surface temperatures off northeastern Australia and associations with rainfall in Queensland: 1956–1987. *International Journal of Climatology* 12, 765–782.

31 Lough JM (1993) Variations of some seasonal rainfall characteristics in Queensland, Australia: 1921–1987. *International Journal of Climatology* 13, 391–409.

32 Lough JM (1994) Climate variation and El Niño-Southern Oscillation events on the Great Barrier Reef. 1958–1987. *Coral Reefs* 13, pp. 181–195.

33 Lough JM (1997) Regional indices of climate variation: temperature and rainfall in Queensland, Australia. *International Journal of Climatology* 17, 55–66.

34 Lough JM (1999) Sea surface temperatures on the Great Barrier Reef: a contribution to the study of coral bleaching. In *GBRMPA Research Publication No. 57*, Great Barrier Reef Marine Park Authority, Townsville.

35 Lough JM (2001) Climate variability and change on the Great Barrier Reef. In: E Wolanski (ed.) *Oceanographic Processes of Coral Reefs. Physical and Biological Links in the Great Barrier Reef*. CRC Press, Boca Raton, pp. 269–300.

36 Lough JM, Berkelmans R, van Oppen M, Wooldridge S and Steinberg C (2006) The Great Barrier Reef and Climate Change. *Bulletin Australian Meteorological and Oceanographic Society* 19, 53–58.

37 Mantua NJ, Hare SR, Zhang Y, Wallace JM and Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin American Meteorological Society* 78, 1069–1079.

38 McBride JL (1987) The Australian summer monsoon. In: C-P Chang, and TN Krishnamurti (eds) *Monsoon Meteorology*, Oxford University Press, New York, pp. 203–231.

39 McInnes KL, Walsh KJE, Hubbert GD and Beer T (2003) Impact of sea level rise and storm surges on a coastal community. *Natural Hazards* 30, 187–207.

40 McPhaden MJ (2004) Evolution of the 2002/03 El Niño. Bulletin American Meteorological Society 85, 677–695.

41 McPhaden MJ, Zebiak SE and Glantz MH (2006) ENSO as an integrating concept in earth science. *Science* 314, 1740–1745.

42 Meehl GA (1987) The annual cycle and interannual variability in the tropical Pacific and Indian Ocean regions. *Monthly Weather Review* 115, 27–50.

43 Meehl GA, Washington WM, Collins WD, Arblaster JM, Hu A, Buja LE, Strand WG and Teng H (2005) How much more global warming and sea level rise? *Science* 307, 1769–1772.

44 Menzel A, Sparks TH, Estrella N, Koch E, Aasa A, Ahas R, Alm-Kübler K, Bissolli P, Braslavská O, Briede A, Chmielewski FM, Crepinsek Z, Curnel Y, Dahl Å, Defila C, Donnelly A, Filella Y, Jatczak K, Måge F, Mestre A, Nordli Ø, Peñuelas J, Pirinen P, Remišová V, Scheifinger H, Striz M, Susnik A, Van Vliet AJH, Wielgolaski F-E, Zach S and Zust A (2006) European phonological response to climate change matches the warming pattern. *Global Change Biology* 12, 1969–1976.

45 Moise AF, Colman RA and Zhang H (2005) *Coupled model simulations of Australian surface precipitation and temperature and their response to global warming in 18 CMIP2 models*. Bureau of Meteorology Research Centre Report No. 106, Bureau of Meteorology.

46 Nakicenovic N and Swart R (eds) (2000) *IPCC Special Report on Emissions Scenarios*. Cambridge University Press, Cambridge.

47 National Tidal Centre - Bureau of Meteorology (2006) *The Australian Baseline Sea Level Monitoring Project. Monthly Data Report. May 2006*. Bureau of Meteorology, Australia (http://www.bom.gov.au/oceanography/projects/abslmp/reports.shtml), 24pp.

48 Nicholls N (2004) The changing nature of Australian droughts. *Climatic Change* 63, 323–336.

49 Nicholls N, Landsea C and Gill J (1998) Recent trends in Australian region tropical cyclone activity. *Meteorology and Atmospheric Physics* 65, 197–205.

50 Parmesan C (2006) Ecological and evolutionary responses to recent climate change. *Annual Reviews of Ecology, Evolution, and Systematics* 37, 637–669.

51 Pittock AB (ed) (2003) *Climate Change: An Australian Guide to the Science and Potential Impacts*. Australian Greenhouse Office, Commonwealth of Australia, Canberra.

52 Power S, Folland C, Colman A and Mehta V (1999) Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics* 15, 319–324.

53 Puotinen ML, Done TJ and Skelly WC (1997) *An Atlas of Tropical Cyclones in the Great Barrier Reef Region, 1969-1997*. CRC Reef Research Centre Technical Report No. 19. CRC Reef Research Centre, Townsville.

54 Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC and Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research* 108 (D14), doi: 10.1029/2002JD002670.

55 Royal Society (2005) *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide*. The Royal Society; London.

56 Sabine CL, Feely RA, Gruber N, Key RM, Lee KM Bullister JL, Wanninkhof R, Wong CS, Wallace DWR, Tilbrook B, Millero FJ, Peng T-H, Kozyr A, Ono T and Rios AF (2004) The oceanic sink for anthropogenic CO_2. *Science* 305, 367–371.

57 Steffen W (2006) *Stronger Evidence but New Challenges: Climate Change Science 2001-2005*. Australian Greenhouse Office, Department of Environment and Heritage, Canberra.

58 Steffen W, Love G and Whetton P (2006) Approaches to defining dangerous climate change: an Australian perspective. In: HJ Schellnhuber (ed) *Avoiding Dangerous Climate Change*. Cambridge University Press, Cambridge, pp. 219–225.

59 Stern H, de Hoedt G and Ernst J (2000) Objective classification of Australian climates. *Australian Meteorological Magazine* 49, 87–96.

60 Sturman A and Tapper N (1996) *The Weather and Climate of Australia and New Zealand*. Oxford University Press, Melbourne.

61 Suppiah R (1992) The Australian summer monsoon: a review. *Progress in Physical Oceanography* 16, 283–318.

62 Turley C, Blackford JC, Widdicombe S, Lowe D, Nightingale PD and Rees AP (2006) Reviewing the impact of increased atmospheric CO_2 on oceanic pH and the marine ecosystem. In: HJ Schellnhuber (ed) *Avoiding Dangerous Climate Change,* Cambridge University Press, Cambridge, pp 65–70.

63 Velicogna I and Wahr J (2006) Acceleration of Greenland ice mass loss in spring 2004. *Nature* 443, 329–331.

64 Walsh K, Hennessy K, Jones R, McInnes KL, Page CM, Pittock AB, Suppiah R and Whetton P (2001) *Climate change in Queensland under enhanced greenhouse conditions – Third Annual Report, 1999-2000*. CSIRO consultancy report for the Queensland Government.

65 Walsh K, Cai W, Hennessy K, Jones R, McInnes K, Nguyen K., Page C and Whetton P (2002) *Climate Change in Queensland under enhanced Greenhouse Conditions*. Final Report. CSIRO Atmospheric Research, Hobart.

66 Walsh KJ, Nguyen KC and McGregor JL (2004) Fine-resolution regional climate model simulations of the impact of climate change on tropical cyclones near Australia. *Climate Dynamics* 22, 47–56.

67 Wang C and Picaut J (2004) Understanding ENSO physics – a review. In: Earth's Climate: *The Ocean-Atmosphere Interaction, Geophysical Monograph Series* 147, American Geophysical Union, pp 21–48.

68 Webster PJ, Holland GJ, Curry JA and Chang H-R (2005) Change in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309, 1844–1846.

69 Whetton PH, McInnes KL, Jones RN, Hennessy KJ, Suppiah R, Page CM, Bathols J and Durack PJ (2005) *Australian climate change projections for impact assessment and policy application: a review*. CSIRO Marine and Atmospheric Research Paper No. 1, CSIRO Marine and Atmospheric Research, Aspendale.

70 Wigley TML (2005) The climate change commitment. *Science* 307, 1766–1769.

71 Wilby RL and Wigley TML (1997) Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography* 21, 530–548.

72 WMO (World Meteorological Organization) (2002) *Scientific Assessment of Ozone Depletion: 2002*. Global Ozone Research and Monitoring Project – Report No. 47, Geneva.

73 Woodruff SD, Lubker SJ, Wolter K, Worley SJ, and Elms JD (1993) Comprehensive Ocean-Atmosphere Data Set (COADS) Release 1a: 1980-1992. *Earth System Monitor* 4, 4–8.

Appendix 2.1
IPCC Special Report on Emissions Scenarios storylines (Nakicenovic and Swart 2000)

A1 storyline – describes a future world of very rapid economic growth, global population peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

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

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

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

Table A1 *Atmospheric concentration of carbon dioxide (CO_2 parts per million), global temperature rise (T°C) above 1961 to 1990 average, and sea level rise (SL cm) above 1961 to 1990 level for four SRES storylines for 2020s, 2050s and 2080s*

	2020s			2050s			2080s		
	CO_2	T	SL	CO_2	T	SL	CO_2	T	SL
B1	421	0.6	7	479	0.9	13	532	1.2	19
B2	429	0.9	20	492	1.5	36	561	2.0	53
A1	448	1.0	21	555	1.8	39	646	2.3	58
A2	440	1.4	38	559	2.6	68	721	3.9	104