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Queensland's biodiversity under climate change:

an overview of climate change in Queensland

Climate Adaptation Flagship Working Paper #12A

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September 2012

National Library of Australia Cataloguing-in-Publication entry

Title:	Queensland's biodiversity under climate change: an overview of climate change in Queensland / Kristen J Williams
ISBN:	978-0-643-10929-2 (pdf)
Series:	CSIRO Climate Adaptation Flagship Working Paper series; 12A.
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Citation

This document can be cited as:

Williams, K.J. and Crimp, S. (2012) *Queensland's biodiversity under climate change: an overview of climate change in Queensland.* CSIRO Climate Adaptation Flagship Working Paper No. 12A. http://www.csiro.au/resources/CAF-working-papers.html

Acknowledgements

This work was funded by the Queensland Government and by the CSIRO through the Climate Adaptation Flagship (Managing Species and Ecosystems Theme).

Comments and peer review by Alistair Hobday, Craig James and Wenju Cai improved this report. Appendix 1 figures were kindly arranged by Elvira Poloczanska. Thanks to Serena Henry for proof reading.

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PREAMBLE

This report is one of seven background documents prepared by the CSIRO Climate Adaptation Flagship for the Queensland Government. Content from this report contributed to the synthesis report titled “Queensland's biodiversity under climate change: impacts and adaptation” by Williams *et al.* (2012a).

The seven background reports are:

A. Overview of climate change in Queensland (Williams & Crimp 2012)

B. Ecological scaling of terrestrial environmental change (Ferrier *et al.* 2012)

C. Terrestrial ecosystems (Murphy *et al.* 2012)

D. Freshwater aquatic ecosystems (Kroon *et al.* 2012)

E. Coastal and marine ecosystems (Bustamante *et al.* 2012)

F. Ecosystem services (Williams *et al.* 2012b)

G. Adaptation principles and options (Dunlop *et al.* 2012)

View over beach, Port Douglas, Queensland (credit: Fiona Henderson, CSIRO Ecosystem Sciences, science image DA11404).

EXECUTIVE SUMMARY

This background report presents a brief overview of observed trends in climate change and projections for Queensland. It provides context for the discussion of ecological change as a result of climate change in the other background reports.

Overwhelming scientific evidence can now be found that links growing concentrations of greenhouse gases to changes in both global and regional climates.

Over the last 50 years, terrestrial regions of Queensland have warmed more than the Australian average with significant declines in rainfall across the central and coastal regions of the State over the same period. Projected temperature increases for Queensland regions by 2050 are in the range of 1–1.4°C for a low emissions scenario (B1) and 1.7–2.2°C for a high emissions scenario (the ‘A1FI’ scenario), with annual rainfall projected to decline by up to 5% for the low emissions scenario and up to 10% for the high emissions scenario.

The number of ‘exceptionally hot’ years in Queensland is projected to increase from a baseline of one event every 22 years (mean for the period 1950 to 2009) to an average of one event every three years by 2050. Climate change is also likely to affect extreme rainfall across much of the coastal high rainfall zone. Tropical cyclone intensity may increase across the northern parts of the country.

These observed changes in atmospheric and climatic conditions have different implications for the types of change in environmental conditions occurring in terrestrial, marine and freshwater aquatic ecosystems (described in Bustamante *et al.* 2012; Kroon *et al.* 2012; Murphy *et al.* 2012).

In particular, ocean mass provides a sink for greenhouse gasses and thermal absorption. Surface warming has been observed over the oceans adjacent to Queensland, with greatest warming in the south of approximately 1°C degree per 100 years and 3–4°C in the north. Over the twentieth century, global sea level increased at an annual average rate of about 2mm each year, commensurate with ocean warming and thermal expansion. Significant increases in coastal inundation can be expected with higher mean sea level and more intense weather systems. Absorption of atmospheric CO_2 by ocean waters leads to acidification with significant feedback effects on the capacity of the ocean to continue to act as buffer and changed geochemistry inhibits growth of some species. Further details about these phenomena and projections of change in the marine environment are given in Bustamante *et al.* (2012).

INTRODUCTION

Overwhelming scientific evidence can now be found that links growing concentrations of greenhouse gases to changes in both global and regional climate (CSIRO & BOM 2007a; Houghton *et al.* 2001; IPCC 2007; Solomon *et al.* 2007). At both national and regional scales, considerable evidence exists for related changes in temperature and rainfall in Australia (Alexander *et al.* 2007; CSIRO & BOM 2007a; Nicholls 2006; Nicholls 2007; Nicholls & Collins 2006; Trewin & Vermont 2010). In this section we present some of the evidence linking greenhouse gas emissions to global warming and climate change, and provide an overview of observed and projected changes in Australia and Queensland's climate. These changes in climate are important underpinnings of environmental change and the response by ecological systems to that change. Further details of the environmental and ecological changes that ensue from climate change are presented in for each of the biological realms – terrestrial, freshwater aquatic, and coastal and marine ecosystems (Bustamante *et al.* 2012; Kroon *et al.* 2012; Murphy *et al.* 2012).

CLIMATE CHANGE CONTEXT

Overwhelming scientific evidence can now be found that links growing concentrations of greenhouse gases to changes in both global and regional climates (CSIRO & BOM 2007a; Houghton *et al.* 2001; IPCC 2007; Solomon *et al.* 2007). As stated by the IPCC (2007): *warming of the climate system is unequivocal as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level*. Subsequent scientific reports have only further emphasized the magnitude and pace of observed and expected change.

During the 20th Century, greenhouse gas concentrations in the atmosphere have increased as a result of growing energy use and expansion of the global economy. Over that century, industrial activity grew 40-fold, and the emissions of gases such as carbon dioxide (CO_2) and sulphur dioxide (SO_2) grew 10-fold (WMO 2011).

The concentration of CO_2 in the atmosphere has increased since pre-industrial times from approximately 280 parts per million by volume (ppmv) at the beginning of the 20th century to 387 ppmv by the end of 2010 (Figure 1), and at current emission rates is expected to reach double pre-industrial levels by about 2070 (Hay 2011). The amount of atmospheric CO_2 varies within each year as a result of the annual seasonal cycles of photosynthesis and oxidation (Figure 1).

Of the other greenhouse gases, methane (CH_4)—which is formed by anaerobic decomposition of organic matter—rose from a preindustrial atmospheric concentration of around 700 parts per billion by volume (ppbv) to about 1,789 ppbv by 2007 (WMO 2011). Other important greenhouse gases include the oxides of nitrogen, notably nitrous oxide (N_2O) and halocarbons, including the chlorofluorocarbons (CFCs) and other chlorine and bromine containing compounds.

The build-up of greenhouse gases in the atmosphere alters the radiative balance of the atmosphere (IPCC 2007). The net effect is to warm the Earth's surface and the lower atmosphere because greenhouse gases absorb some of the Earth's outgoing heat radiation and reradiate it back towards the surface. The overall warming from 1850 to the end of the 20th century was equivalent to about 2.5 watts per square metre (W/m^2); CO_2 contributed some 60 per cent of this figure and CH_4 about 25 per cent, with N_2O and halocarbons providing the remainder (WMO 2011). This has resulted in Earth's average temperature increasing from 15.5°C to 16.2°C in the last 100 years. The warming effect that would result from a doubling of CO_2 from pre-industrial levels is estimated to be 4 W/m² (WMO 2011).

The ocean mass provides a sink for greenhouse gasses, but absorption of atmospheric CO_2 leads to acidification of ocean waters (Sabine *et al.* 2004). Between 1751 and 1994 surface ocean pH is estimated to have decreased globally from approximately 8.25 to 8.14 (Figure 2 and Figure 3), representing an increase of approaching 30% in "acidity" (hydrogen ion concentration) (Orr *et al.* 2005; Sabine *et al.* 2004). As surface waters become more acidic, the concentration of carbonate ions decreases while bicarbonate and hydrogen ion concentrations increase. This change in chemical equilibrium causes a reduction of the capacity of the ocean to take up additional CO_2 (Bindoff *et al.* 2007).

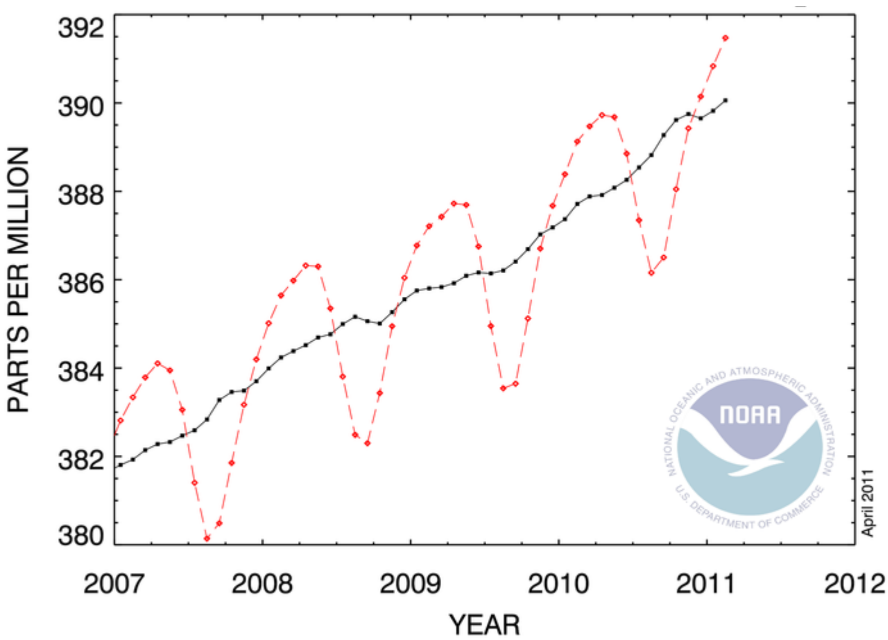


Figure 1: Recent trends in monthly mean carbon dioxide globally averaged over marine surface sites, downloaded from http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html.

The Global Monitoring Division of NOAA/Earth System Research Laboratory has measured carbon dioxide and other greenhouse gases for several decades at a globally distributed network of air sampling sites (Conway *et al.* 1994). A global average is constructed by first fitting a smoothed curve as a function of time to each site, and then the smoothed value for each site is plotted as a function of latitude for 48 equal time steps per year. A global average is calculated from the latitude plot at each time step (Masarie & Tans 1995). The dashed red line with diamond symbols represents the monthly mean values, centred on the middle of each month. The black line with the square symbols represents the same, after correction for the average seasonal cycle. The latter is determined as a moving average of 7 adjacent seasonal cycles centred on the month to be corrected, except for the first and last 3½ years of the record, where the seasonal cycle has been averaged over the first and last 7 years, respectively.

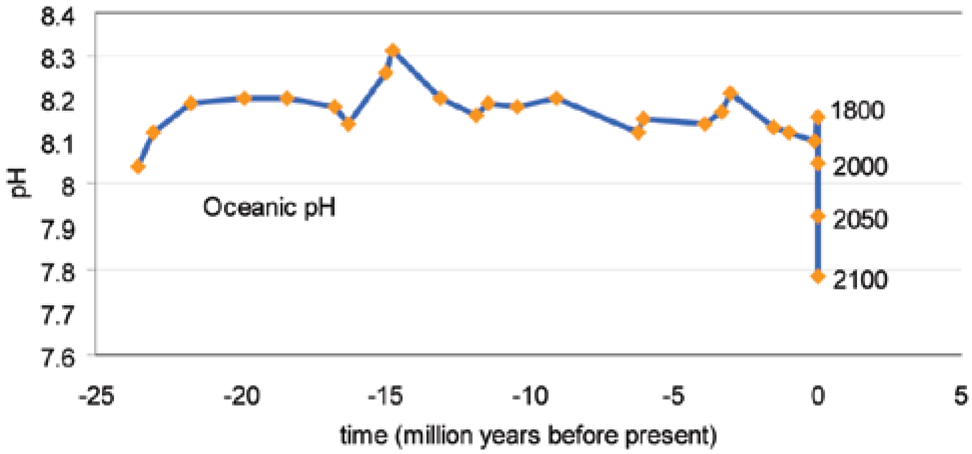


Figure 2: Past and present variability of marine pH. Future predictions for years shown on the right-hand side of the figure are model-derived values based on IPCC mean scenarios (IPCC 2007).

From Pearson and Palmer (Pearson & Palmer 2000), adapted by Turley *et al.* (Turley *et al.* 2006) and from the Eur-Oceans Fact Sheet No. 7, "Ocean Acidification - the other half of the CO2 problem", May 2007 (Blackford *et al.* 2007).

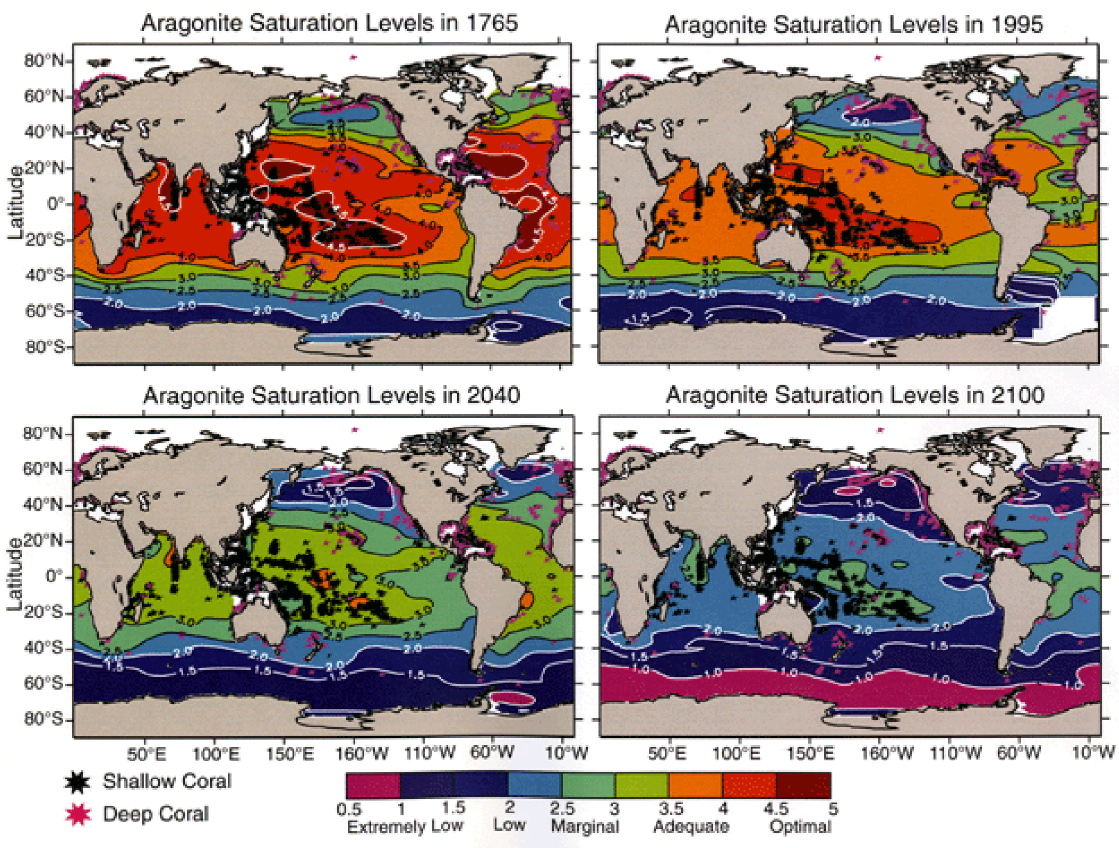


Figure 3: Aragonite saturation levels from before the industrial revolution to 2100 and how these saturation levels affect the growth of both shallow and deep corals.

Figure derived from Feely et al. (2006). Models based on the work of Orr et al. (2005). Before the industrial revolution, we see large bands of the tropical ocean that are optimal for coral growth. By 2040, these same bands are only adequate, and by 2100 most areas are marginal at best.

OBSERVED CLIMATE CHANGE

At both national and regional scales, considerable evidence exists for related changes in temperature and rainfall in Australia (e.g., Alexander *et al.* 2007; Cai & Cowan 2008; Cai *et al.* 2011; Cai *et al.* 2003; Cai & Cowan 2006; CSIRO & BOM 2007a; Nicholls 2006; Nicholls 2007; Nicholls & Collins 2006; Trewin & Vermont 2010) as well as how these changes will continue in the future (CSIRO & BOM 2007a; Houghton *et al.* 2001; Solomon *et al.* 2007). On a global basis, most of the warming has occurred since the 1970s (Figure 4). Warming in the 30°N to 30°S latitudinal range (Figure 6) is stronger than the southern hemisphere warming (Figure 5). This could be due to the greater warming over land and the large amount of land in the low to mid latitudinal range, particularly in the northern hemisphere.

Over the last 50 years, Queensland, located within the tropical belt from latitude 10 to 30°S, has warmed more readily than the Australian average (Whitfield *et al.* 2010), with annual mean temperature increases of approximately 0.5°C since the mid-1970s and about 1°C since the turn of the century (Figure 7, Figure 8). Much of the warming is attributed to rapid increases in minimum temperatures Figure 9—approximately 30% more warming than maximum temperatures (Nicholls 2004). While warming has occurred in all seasons, the strongest trend has occurred in winter and spring (e.g., Figure 10).

Substantial warming has occurred in the three oceans surrounding Australia, and the warming of surface waters of the Coral Sea surrounding Queensland are indicative of the change (Figure 11). In the Pacific, an El Niño-like pattern features prominently in the warming trend with a stronger warming in the eastern Pacific (CSIRO & BOM 2007a). It is not yet clear how the pattern is responding to greenhouse gas induced global warming (Cai *et al.* 2010a).

Increased air temperatures, and possibly higher radiation due to decreased cloudiness, will increase potential evapotranspiration (the amount of water that could evaporate and transpire from plants if sufficient water was available) in Queensland, and thus increase evaporation under future warming (CSIRO & BOM 2007a; Whitfield *et al.* 2010). Contrary to this, pan evaporation which measures the quantity of water evaporated from a small open water surface, shows a slightly decreasing trend, mostly non-significant across Australia, despite the warming trend that Australia has experienced in the last decades (Jovanovic *et al.* 2008). The trend map in annual pan evaporation during the period 1970-2010 shows a larger decrease across the northern half of Queensland as compared to the southern part (Figure 12). It is not conclusive how this trend will transform into future scenarios. Whilst for open water bodies no significant trend for evaporation can be established, this does not rule out a possible future change in evaporation (Fu *et al.* 2009; Gifford 2005).

Since the 1960s, Queensland has experienced declining annual rainfall in some populated coastal regions and increases in northern and inland regions (Figure 13) (CSIRO & BOM 2007a; CSIRO & BOM 2010). Much of this decline in annual rainfall is attributed to an increase in the frequency of El Niño – Southern Oscillation (ENSO) like conditions in the Pacific Ocean (Cai *et al.* 2010b; Power *et al.* 2006). Intense periods of rainfall may occur during La Nina events that sometimes extend through summer (Figure 14) with increased cyclone activity (Figure 15) linked to sea surface temperatures (Elsner *et al.* 2008), contrasting with severe rainfall deficits that may be experienced during extended El Nino events (Nicholls 2004). The coincidence of intense tropical cyclones and high tide events exacerbates local flooding and erosion in the coastal zone (QCCCE 2011). For example, storm surge studies for the Queensland coast demonstrate the potential for significant increases in inundation due to higher mean sea level and more intense weather systems (Hardy *et al.* 2004; Whitfield *et al.* 2010) leading to the identification of specific coastal hazard areas (Environment Planning 2011; QCCCE 2011).

Over the twentieth century, global sea level increased at an annual average rate of about 2mm each year (Willis *et al.* 2010), commensurate with ocean warming and thermal expansion. Over the last two decades, evidence from tide gauge and satellite altimetry data suggests annual average sea level rise has accelerated to about 3mm each year, in part attributed to increased ocean mass from glacier and polar ice sheet melting (e.g., Cazenave & Llovel 2010; Church & White 2006; Kemp *et al.* 2009). Regional effects of sea level rise are modulated by ocean currents and patterns of atmospheric pressure and bottom topography (see Bustamante *et al.* 2012). For example, over the period 1920 to 2000 the estimated average relative sea level rise around Australia was 1.2 mm each year (Church *et al.* 2006). For planning purposes, the Queensland Government has adopted the IPPC (2007) sea level rise projection of 80cm by 2100 (Environment Planning 2011) and mapped high and medium coastal areas at risk of erosion above and below 1.0m respectively.

These observed changes in atmospheric and climatic conditions have different implications for the types of change in environmental conditions occurring in terrestrial, marine and freshwater aquatic ecosystems (see Bustamante *et al.* 2012; Kroon *et al.* 2012; Murphy *et al.* 2012). Global analyses of the velocity of recent climate change (warming over 50 years, 1960–2009) indicates that local shifts in climatic environments often deviate from the expected trend of poleward expansion and earlier spring events (Burrows *et al.* 2011). Example figures for Australia from this global analysis are presented in Appendix 1.

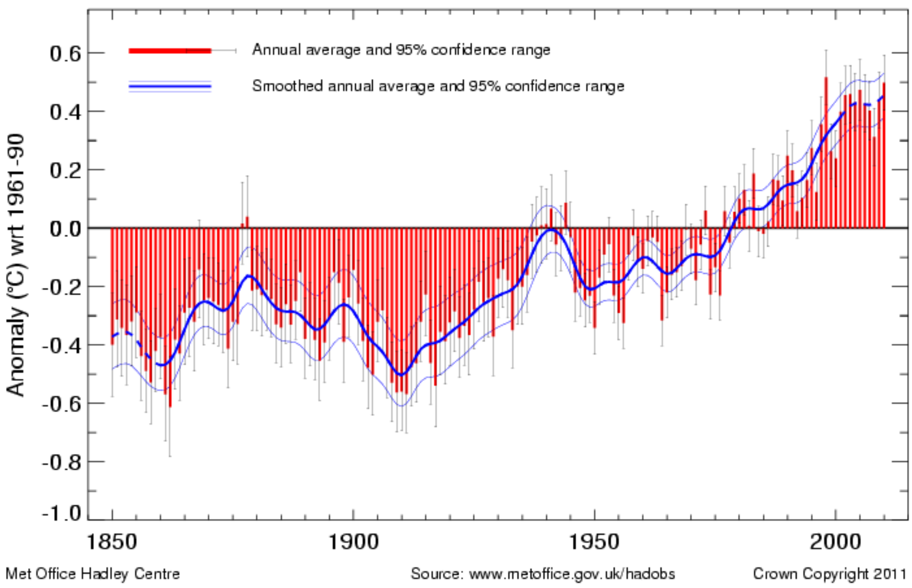


Figure 4: Global average temperature anomalies (1850-2010) from UK Met Office Hadley Centre observations database (HadCRUT3) based on Brohan *et al.* (2006). The red bars show the global annual average near surface temperature anomalies from 1850 on. The error bars show the 95% uncertainty range on the annual averages. The thick blue line shows the annual values after smoothing with a 21 point binomial filter. The dashed portion of the smoothed line indicates where it is influenced by the treatment of the end points (Brohan *et al.* 2006). The thin blue lines show the 95% uncertainty on the smoothed curve. Online: http://www.metoffice.gov.uk/hadobs/hadcrut3/diagnostics/global/nh+sh/.

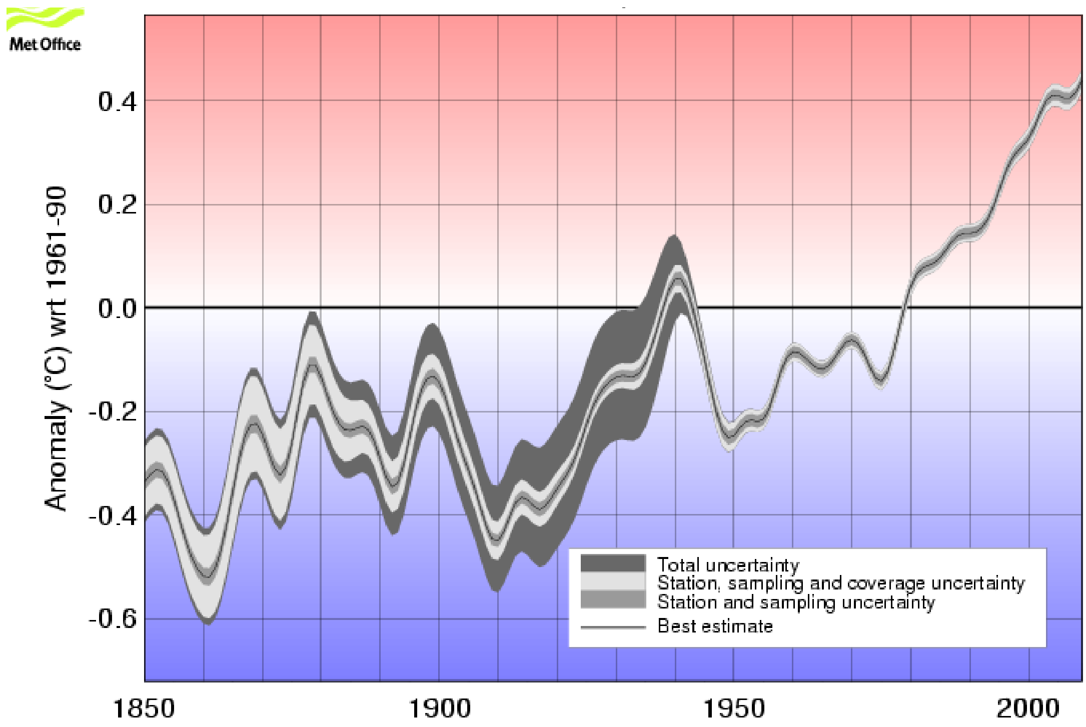
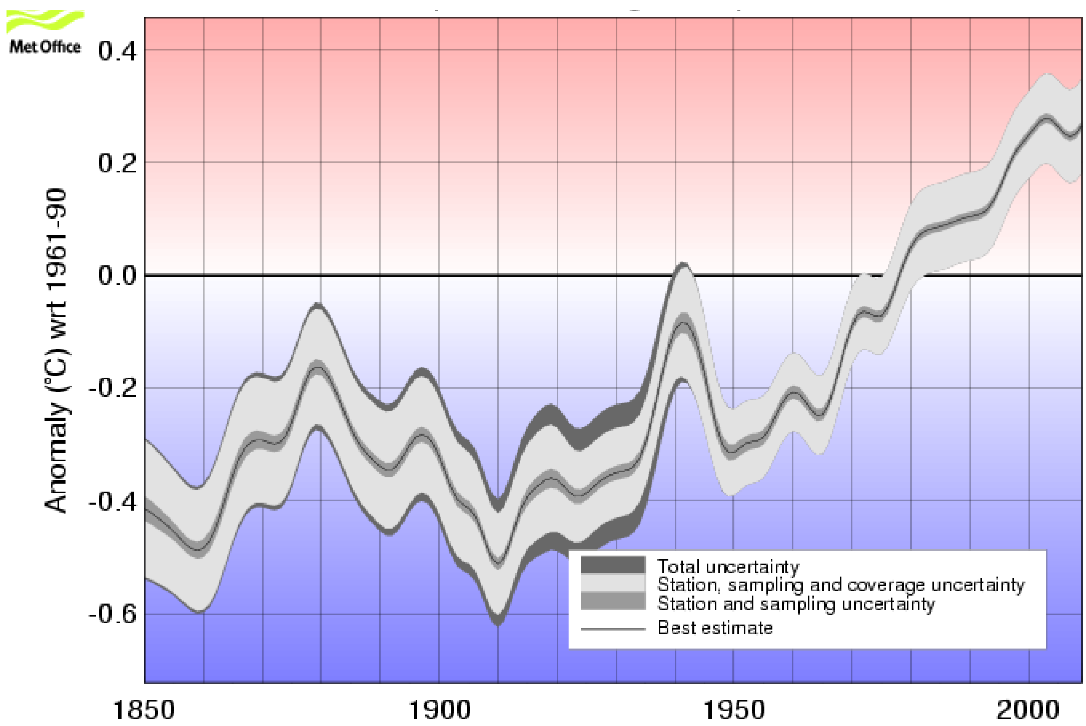


Figure 5: Tropical (30°N-30°S) average temperature anomalies (1850-2010) from UK Met Office Hadley Centre observations database (HadCRUT3) based on Brohan *et al.* (2006): annual series after smoothing with a 21 point binomial filter.



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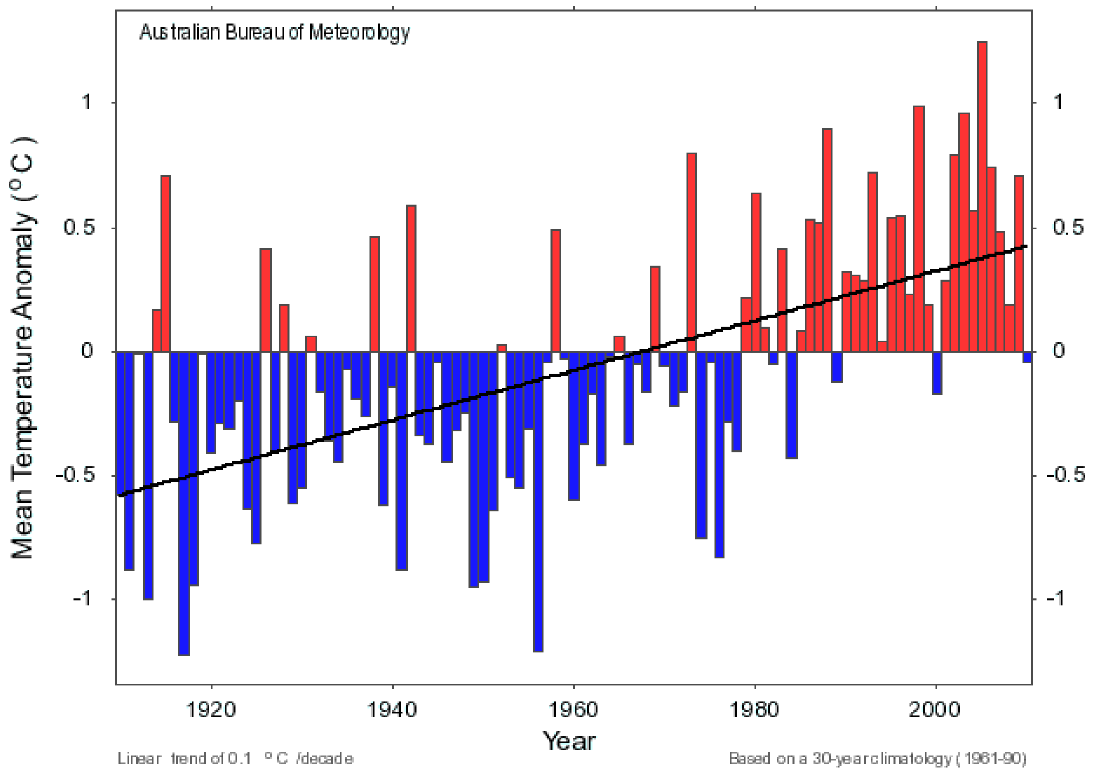


Figure 7: Queensland annual mean temperature anomalies (1910-2010) from Australian Bureau of Meteorology observations database (Della-Marta *et al.* 2004). Time series are presented as anomalies or departures from the 1961-1990 average (the current international standard period for the calculation of climate normals).

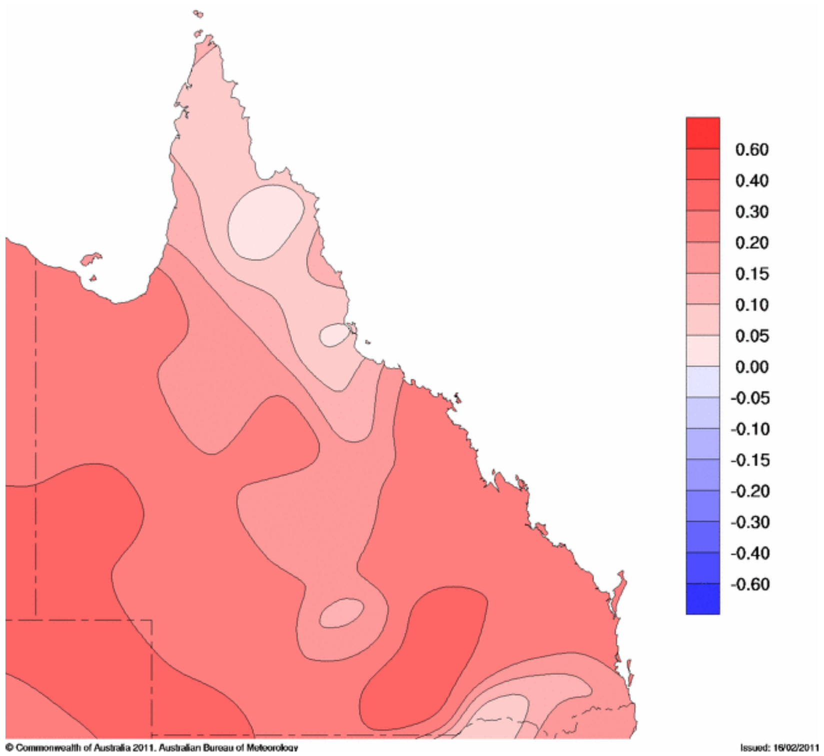
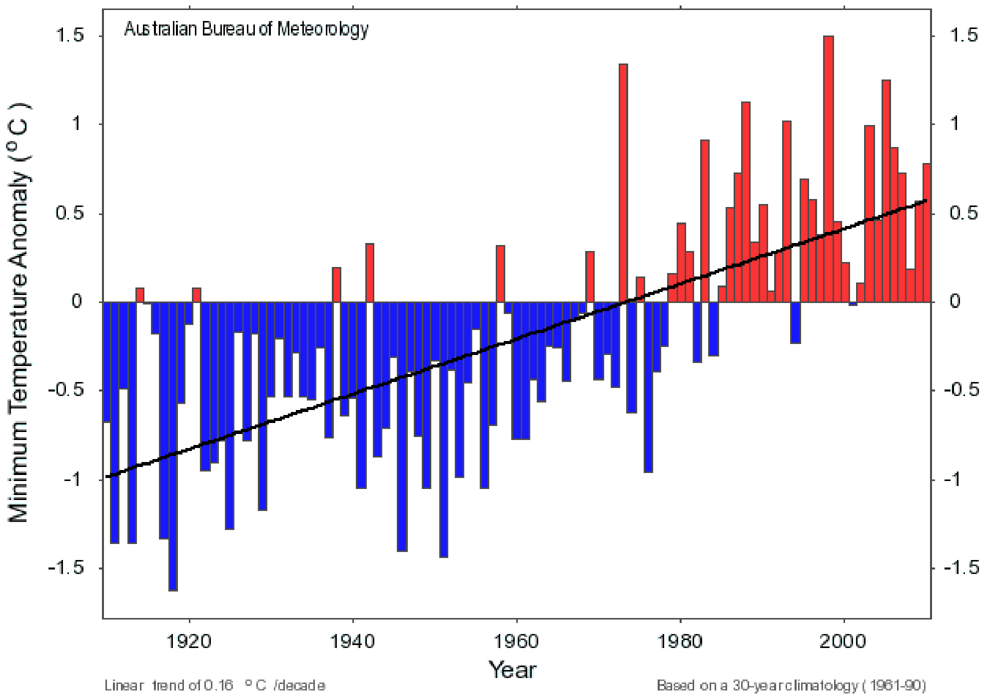


Figure 8: Trend in mean temperature 1970-2010 over Queensland from Australian Bureau of Meteorology observations database (Della-Marta *et al.* 2004).

Trend values have been determined from a linear (straight line) fit to the data, but the change may not have been gradual, and do not imply future rates of change (see http://www.bom.gov.au/climate/change/about/rain_trendmaps.shtml).



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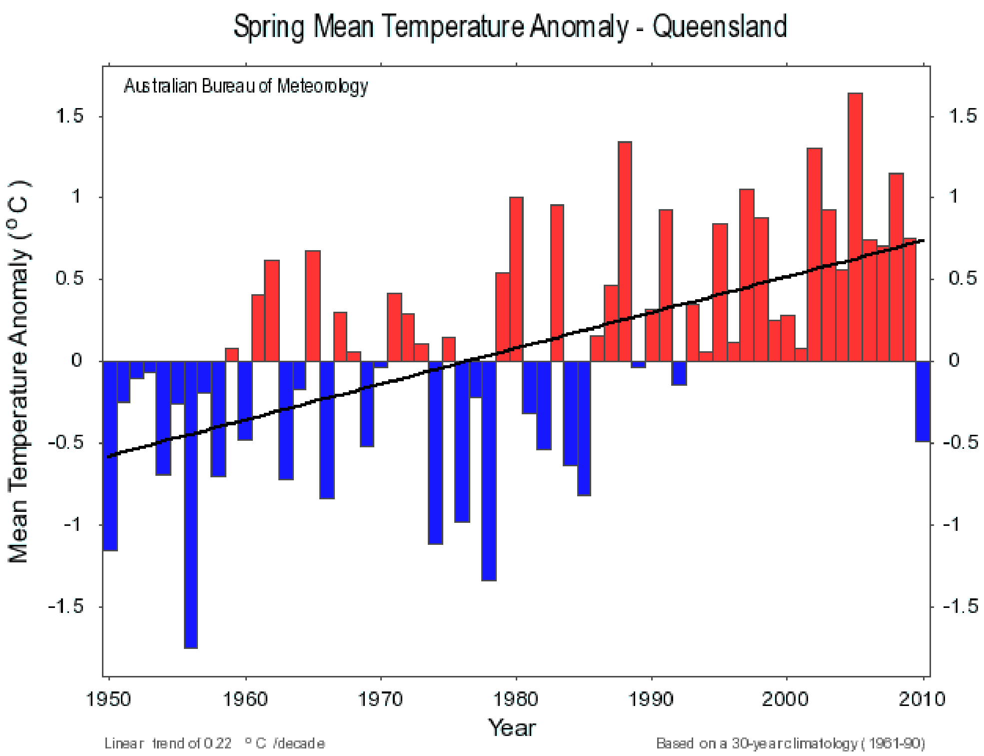

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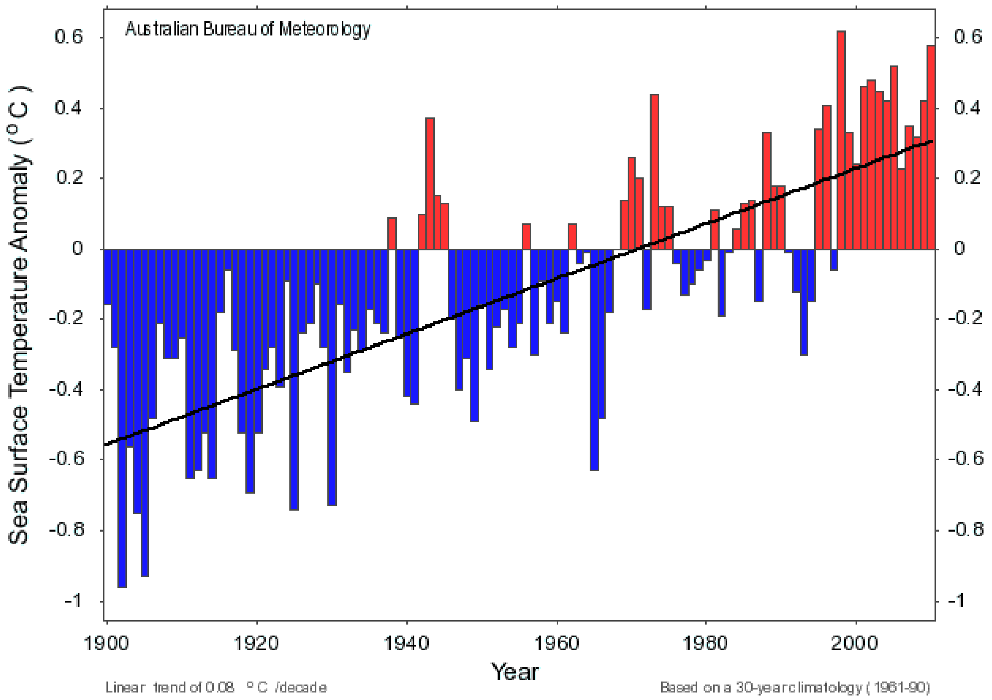

Figure 11: Annual sea surface temperature anomaly for the Coral Sea (1900-2010) from Australian Bureau of Meteorology observations database (Della-Marta *et al.* 2004).

Time series are presented as anomalies or departures from the 1961-1990 average (the current international standard period for the calculation of climate normals). Calculated from the NOAA Extended Reconstructed Sea Surface Temperature Version 3 (NOAA_ERSST_V3) data, http://www.cdc.noaa.gov/ (Smith *et al.* 2008).

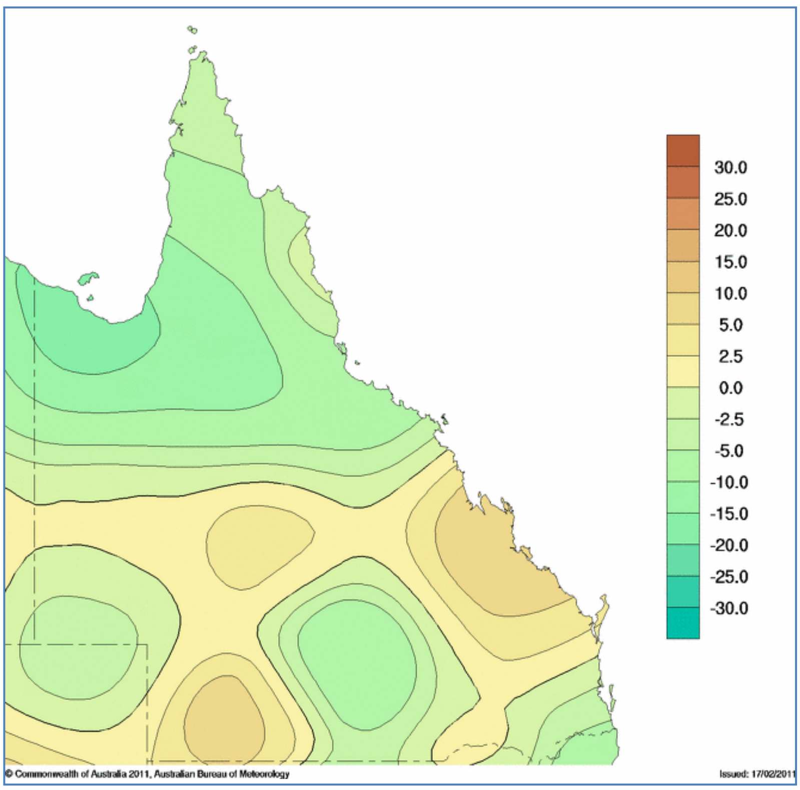

Figure 12: Trend in annual total pan evaporation for Queensland, 1970-2010 (mm/year), published by the Australian Bureau of Meteorology.

The evaporation trend map was calculated from "high-quality" pan evaporation data developed specifically for monitoring long-term trends and variability in Australian evaporation (Jovanovic *et al.* 2008). Trend maps compare how pan evaporation has changed in different regions over time. Trend values have been determined from a linear (straight line) fit to the data, but the change may not have been gradual. For more information see http://www.bom.gov.au/climate/change/about/evap_trendmaps.shtml.

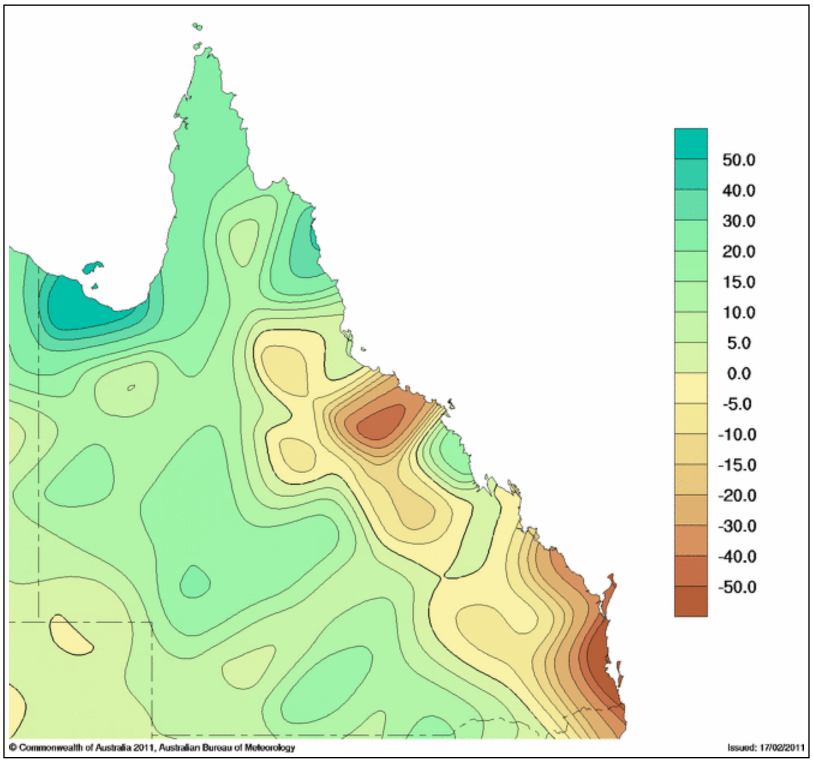

Figure 13: Trend in total annual rainfall for Queensland (1960-2010) from Australian Bureau of Meteorology observations database (Lavery *et al.* 1997).

Trend values have been determined from a linear (straight line) fit to the data, but the change may not have been gradual, and do not imply future rates of change (see http://www.bom.gov.au/climate/change/about/rain_trendmaps.shtml).

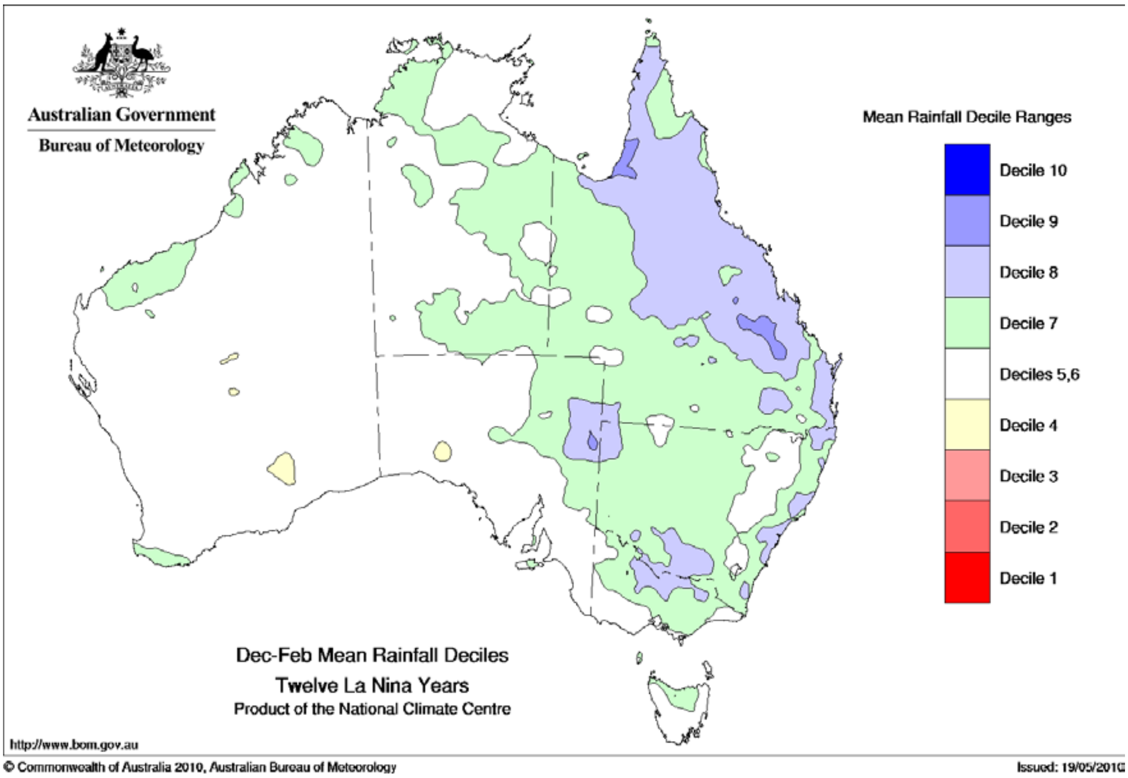

Figure 14: Australian summer mean rainfall deciles for 12 La Nina events (1900-2004) from Australian Bureau of Meteorology observations database (http://www.bom.gov.au/climate/enso/ninacomp.shtml).

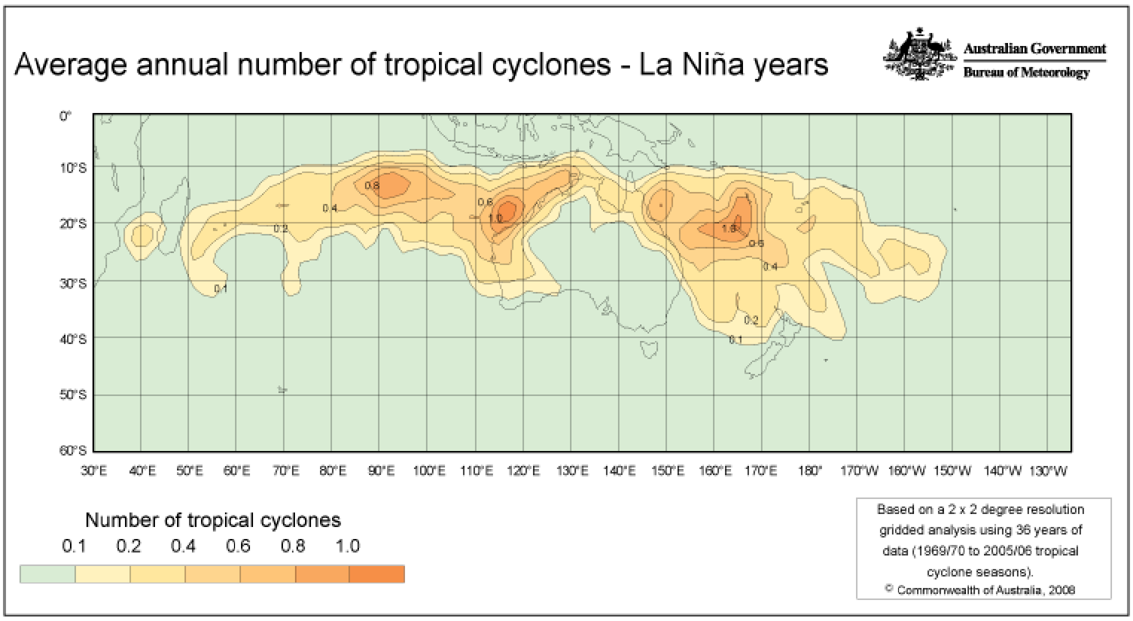

Figure 15: Average annual number of tropical cyclones in La Nina years (1969/70 to 2005/06) from Australian Bureau of Meteorology observations database (Wright 2000) (see, http://www.bom.gov.au/jsp/ncc/climate_averages/tropical-cyclones/index.jsp).

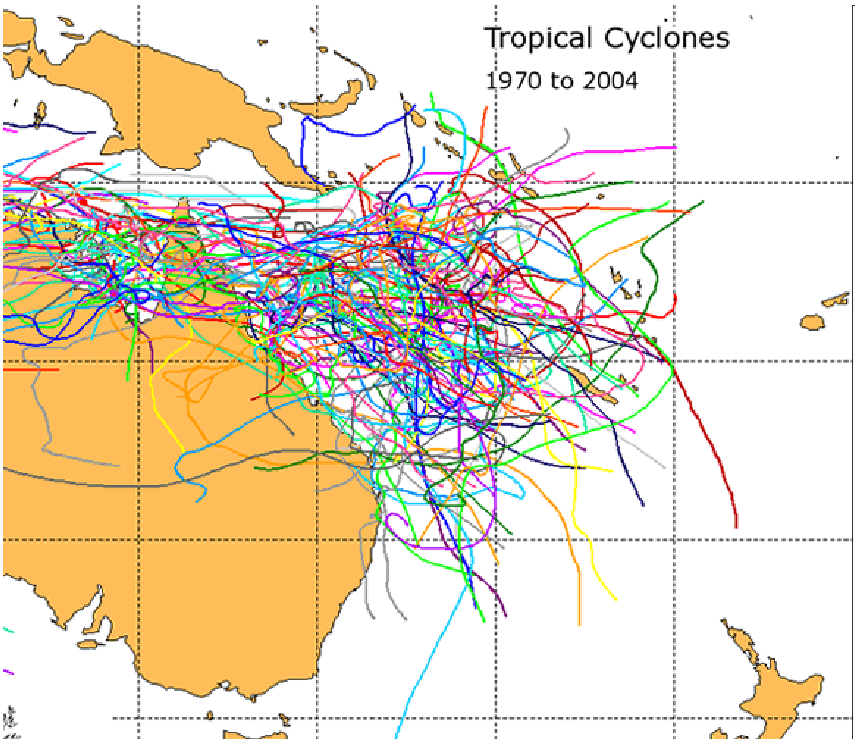

Figure 16: Tropical cyclone tracks for cyclones that formed or moved through the Eastern region from 1970 – 2004. Bureau of Meteorology, http://www.bom.gov.au/cyclone/about/eastern.shtml#history.

PROJECTED CLIMATE TRENDS

As indicated above, human–mediated emissions of greenhouse gasses, dominated by carbon dioxide (CO_2), are one of the mechanisms whereby recent climate change is induced (Kutzbach *et al.* 2010; Solomon *et al.* 2007). The other mechanisms, also attributed to human activity, are 2) global changes to land surface, such as deforestation, and 3) increasing atmospheric concentrations of aerosols (for details, see Forster *et al.* 2007). In 2007, the Intergovernmental Panel on Climate Change released their fourth assessment report (IPCC 2007) in which the climate change impacts of future emission scenarios in IPCC (2000) were updated. The special report on emissions scenarios ("SRES 2000", see IPCC 2000; Nakicenovic *et al.* 2000; Nakicenovic & Swart 2000) is based on four narratives describing alternative futures representing different demographic, social, economic, technological, and environmental developments. These scenarios were quantified using a variety of modelling approaches that represent a specific quantitative interpretation of one of the four storylines. All the scenarios based on the same storyline constitute a scenario "family" (IPCC 2000). The four scenario families (A1, A2, B1 and B2) explore alternative development pathways and resulting greenhouse gas emissions. Without any likelihood attached, the SRES scenarios have been summarised in IPCC (2007) as follows:

- The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B).

- B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy.

- B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social, and environmental sustainability.

- A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change.

Different international groups are simulating changes in future global and regional climate patterns using global climate models (GCMs) driven by these SRES emissions scenarios. For the IPCC Fourth Assessment report 23 GCMs driven with many different emissions scenarios were used to understand potential changes in the future global climate. These multiple projections serve to reflect both the uncertainty regarding future emissions pathways as well as the uncertainty associated with the atmospheric response to enhanced greenhouse gasses (GHGs). Incorporating both these elements of uncertainty results in a wide range of future projections particularly post 2030 when emissions scenarios diverge (Figure 17). Current emissions levels are tracking around the upper range of the A1FI emissions scenarios (Dolman *et al.* 2010; Le Quere *et al.* 2009), which could lead to a warming of 4°C relative to pre-industrial during the 2070s; making this a plausible scenario for climate impact assessment studies (Betts *et al.* 2011). The three IPCC scenarios most often used in climate modelling are: B1 lower emissions growth scenario; A1B medium emissions growth scenario; and A1FI higher emissions growth scenario (for details see Whitfield *et al.* 2010, p. 14). By 2100, the projections for the A2 emissions scenario, which represents a continuously increasing population with a more fragmented and slower uptake of technology, are greater than those of the A1FI scenario (Figure 17).

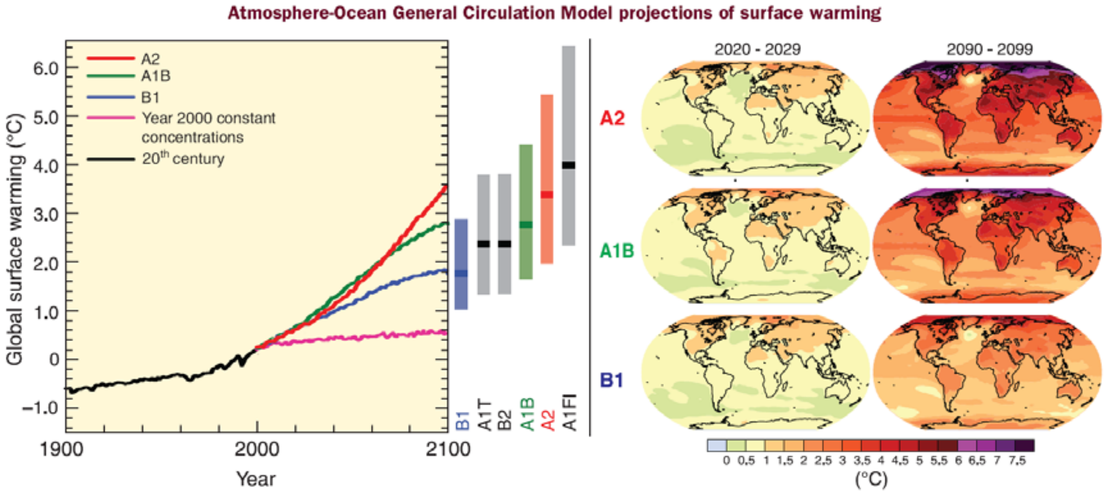

Figure 3.2. Left panel: *Solid lines are multi-model global averages of surface warming (relative to 1980-1999) for the SRES scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. The orange line is for the experiment where concentrations were held constant at year 2000 values. The bars in the middle of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099 relative to 1980-1999. The assessment of the best estimate and likely ranges in the bars includes the Atmosphere-Ocean General Circulation Models (AOGCMs) in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.* ***Right panels:*** *Projected surface temperature changes for the early and late 21st century relative to the period 1980-1999. The panels show the multi-AOGCM average projections for the A2 (top), A1B (middle) and B1 (bottom) SRES scenarios averaged over decades 2020-2029 (left) and 2090-2099 (right). {WGI 10.4, 10.8, Figures 10.28, 10.29, SPM}*

Figure 17: Multi-model global averages and range of surface for three SRES emissions scenarios, reproduced from on Figure 3.2 in IPCC (2007).

If global greenhouse gas emissions continue to grow at rates consistent with past trends, average air temperatures in the Australian region may rise by 0.6–1.5°C by 2030 and by 2.2–5.0°C by 2070 and climates will be drier (CSIRO & BOM 2010). These effects will be superimposed upon natural variability leading to changes in the frequency and intensity of extreme weather events. An overview of the effects of projected climate change over the next 100 years for Queensland is presented by Gilmore *et al.* (2008) and Whitfield *et al.* (2010). Extensive projection information is contained in Queensland's climate change strategy (DERM 2009b). Detailed information regarding future projections of temperature, rainfall and evaporation can be downloaded for 13 regions of the State (DERM 2009a).

Projected temperature increases for Queensland regions by 2050 are in the range 1–1.4°C for the low emissions scenario (B1) and 1.7–2.2°C for the high emissions scenario (A1FI) (Figure 1a and b), with annual rainfall projected to decline by up to 5% for a low emissions scenario and up to 10% for a high emissions scenario (Figure 18c and d).

Comparisons of historical average climates (centred on 1990) and projected future climates (A1B medium climatic sensitivity to emissions in 2030 and A1FI high climatic sensitivity to emissions in 2070) for annual temperature, annual evaporation and rainfall in dry and wet quarters are presented in Kroon *et al.* (2012) in the context of potential freshwater aquatic ecosystem changes. Similar projections for marine systems – seal level rise, sea surface temperatures, acidification, and changing currents systems – are described and mapped Bustamante *et al.* (2012).

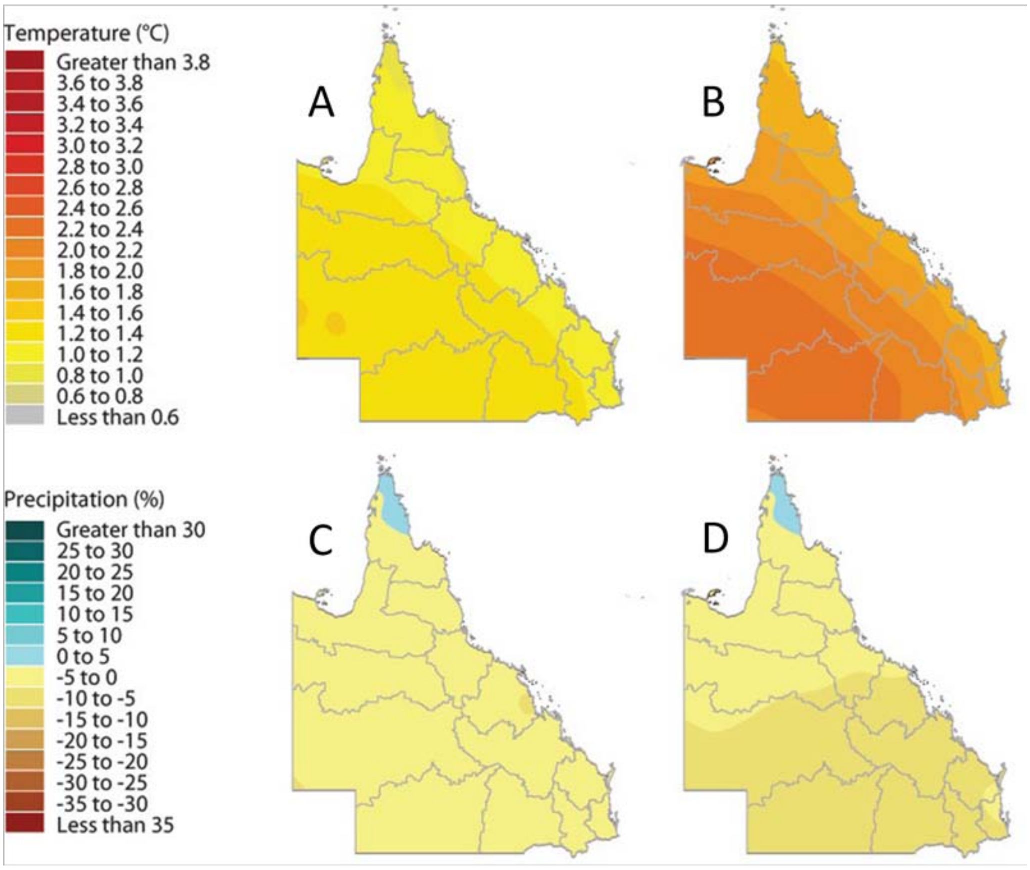

Figure 18: A map showing projected changes by 2050 in a) temperature under a low emissions scenario, b) temperature under a high emissions scenario, c) rainfall under a low emissions scenario and d) rainfall under a high emissions scenario (source: QCCCE - Whitfield *et al.* 2010).

Projected changes in extreme weather events

Projections for Queensland indicate a significant increase in the number of ‘exceptionally hot’ years, from a baseline of 1 event every 22 years (mean for the period 1950 to 2009) to an average of 1 event every 3 years by 2050. Climate change is also likely to affect extreme rainfall across much of the coastal high rainfall zone. A study by Abbs *et al.* (2007) in south-east Queensland found significant increases were likely for 2-hour, 24-hour and 72-hour extreme rainfall events under all future emissions scenarios. Under an A2 emissions scenario, extreme rainfall intensity averaged over the Gold Coast sub-region are projected to increase by 48% for two-hour events, 16% for 24-hour events and 14% for 72-hour events by 2070.

The effect of global warming on the number, duration and intensity of cyclones is not fully clear although most global simulations project an increase in cyclone intensity (Webster *et al.* 2005), while regional models for Queensland project an increase in intensity but potentially an overall decrease in number (CSIRO & BOM 2007b). Simulations for Queensland also show more long-lived tropical cyclones and a southward shift in tropical cyclone genesis and decay areas of between 2 and 3 degrees of latitude (Abbs *et al.* 2006; Leslie *et al.* 2007).

PROJECTED ENVIRONMENTAL CHANGE

The observed and projected changes in atmospheric and climatic conditions will have a range of effects on climatic and environmental conditions and on the physical habitats of biota occurring in terrestrial, marine and freshwater aquatic ecosystems. The biophysical effects of this warming will be manifest in the following atmospheric and climatic factors (IPCC 2007), which are discussed in more detail in the context of environmental change in three background reports (Bustamante *et al.* 2012; Kroon *et al.* 2012; Murphy *et al.* 2012):

- Rising atmospheric CO_2 concentration (Friedlingstein *et al.* 2010) (see Bustamante *et al.* 2012; Murphy *et al.* 2012).

- Rising acidification of water bodies associated with dissolved CO_2 (Caldeira & Wickett 2003; Orr *et al.* 2005) (see Bustamante *et al.* 2012; Kroon *et al.* 2012).

- Sea level rise and coastal erosion (Cazenave & Llovel 2010; Rahmstorf *et al.* 2007; Willis *et al.* 2010) (see Bustamante *et al.* 2012, in particular).

- Variable and declining rainfall (CSIRO & BOM 2007a; Gilmore *et al.* 2008; Whitfield *et al.* 2010) (see Kroon *et al.* 2012; Murphy *et al.* 2012).

- Higher air temperatures, with increased nightly temperatures and lower diurnal ranges (CSIRO & BOM 2007a; Gilmore *et al.* 2008; Whitfield *et al.* 2010) (see Kroon *et al.* 2012; Murphy *et al.* 2012).

- Intensification and increasing frequency of extreme events (tropical cyclones, storm surge, heat waves, rainfall intensity, wildfire) (CSIRO & BOM 2007a; Gilmore *et al.* 2008; Whitfield *et al.* 2010) (see Bustamante *et al.* 2012; Kroon *et al.* 2012; Murphy *et al.* 2012).

- Changes in solar radiation dependent on cloudiness and increased presence of aerosols in the atmosphere (Wild 2010) (see Murphy *et al.* 2012).

- Changes in evaporation due to changes in temperature solar radiation, vapour pressure deficit, cloud cover and wind speed (Fu *et al.* 2009; Roderick & Farquhar 2002; Shen *et al.* 2010), with implications for effective rainfall (see Kroon *et al.* 2012; Murphy *et al.* 2012).

- Increased surface wind speeds in most coastal areas, and extreme wind speed is also likely to increase, but there is also evidence of a stilling effect at mid-latitudes and higher elevations (McVicar *et al.* 2008; McVicar *et al.* 2010) (see Bustamante *et al.* 2012; Kroon *et al.* 2012; Murphy *et al.* 2012).

APPENDIX 1 – THE PACE OF SHIFTING CLIMATE IN MARINE AND TERRESTRIAL ECOSYSTEMS

Example figures for Australia from the global analysis by Burrows *et al.* (2011), courtesy E. Poloczanska.

Figure 19: Seasonal shifts in October sea-surface temperature (SST). The measurement unit for seasonal climate shift in days per decade (days/decade) is calculated as the ratio of the long-term temperature trend (ºC/year) to the seasonal rate of change in temperature (ºC/day) for a warming trend over 50 years (1960–2009). Source: Burrows *et al.* (Burrows *et al.* 2011), courtesy E. Poloczanska.

Figure 20: Seasonal shifts in April sea-surface temperature (SST). The measurement unit for seasonal climate shift in days per decade (days/decade) is calculated as the ratio of the long-term temperature trend (ºC/year) to the seasonal rate of change in temperature (ºC/day) for a warming trend over 50 years (1960–2009). Source: Burrows *et al.* (Burrows *et al.* 2011), courtesy E. Poloczanska.

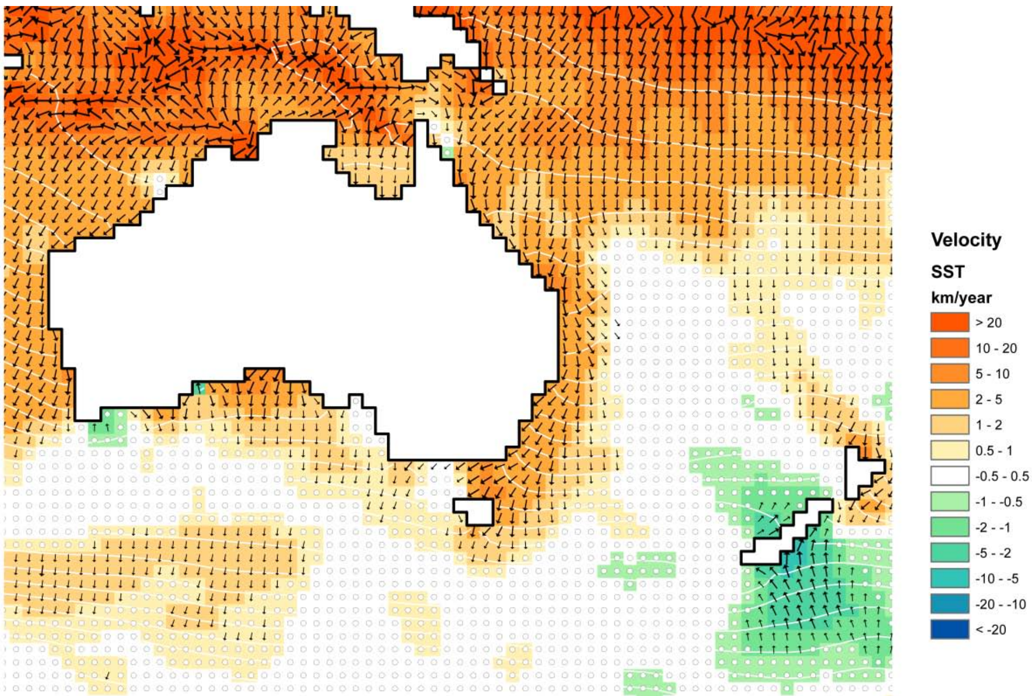

Figure 21: Regional patterns in velocity of sea surface temperature shifts over 50 years (1960–2009). Velocity of isothermal climate change (km/year) was calculated as the ratio of the long-term temperature trend (ºC/year) to the two-dimensional spatial gradient in temperature (ºC/km, calculated over a 3º by 3º grid), oriented along the spatial gradient over 50 years (1960–2009). Source: Burrows *et al.* (Burrows *et al.* 2011), courtesy E. Poloczanska.

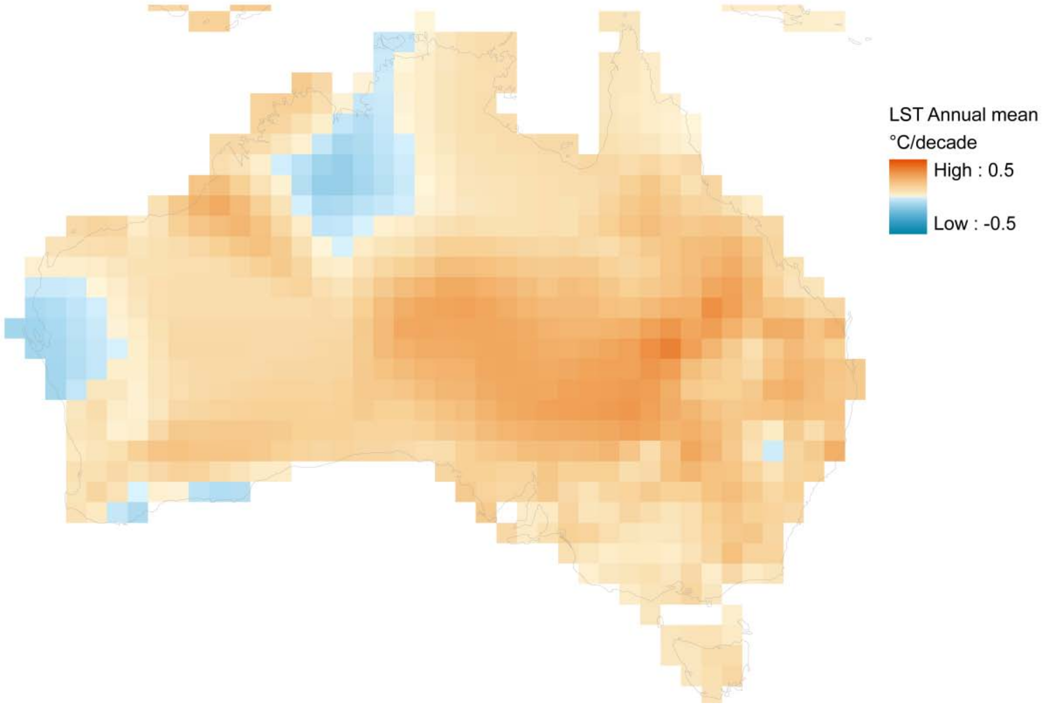

Figure 22: Average annual change in land surface temperature per decade, 1960-2009. Source: Burrows *et al.* (Burrows *et al.* 2011), courtesy E. Poloczanska.

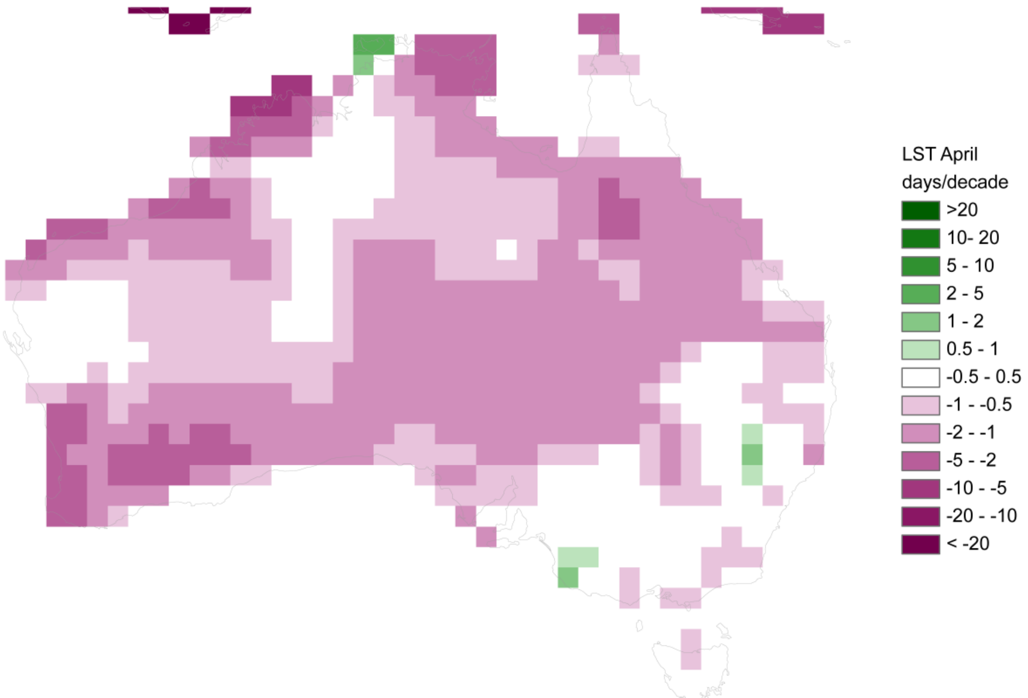

Figure 23: Seasonal shifts in April land-surface temperature (SST). The measurement unit for seasonal climate shift in days per decade (days/decade) is calculated as the ratio of the long-term temperature trend (ºC/year) to the seasonal rate of change in temperature (ºC/day) for a warming trend over 50 years (1960–2009). Source: Burrows *et al.* (Burrows *et al.* 2011), courtesy E. Poloczanska.

Figure 24: Seasonal shifts in October land-surface temperature (SST). The measurement unit for seasonal climate shift in days per decade (days/decade) is calculated as the ratio of the long-term temperature trend (ºC/year) to the seasonal rate of change in temperature (ºC/day) for a warming trend over 50 years (1960–2009). Source: Burrows *et al.* (Burrows *et al.* 2011), courtesy E. Poloczanska.

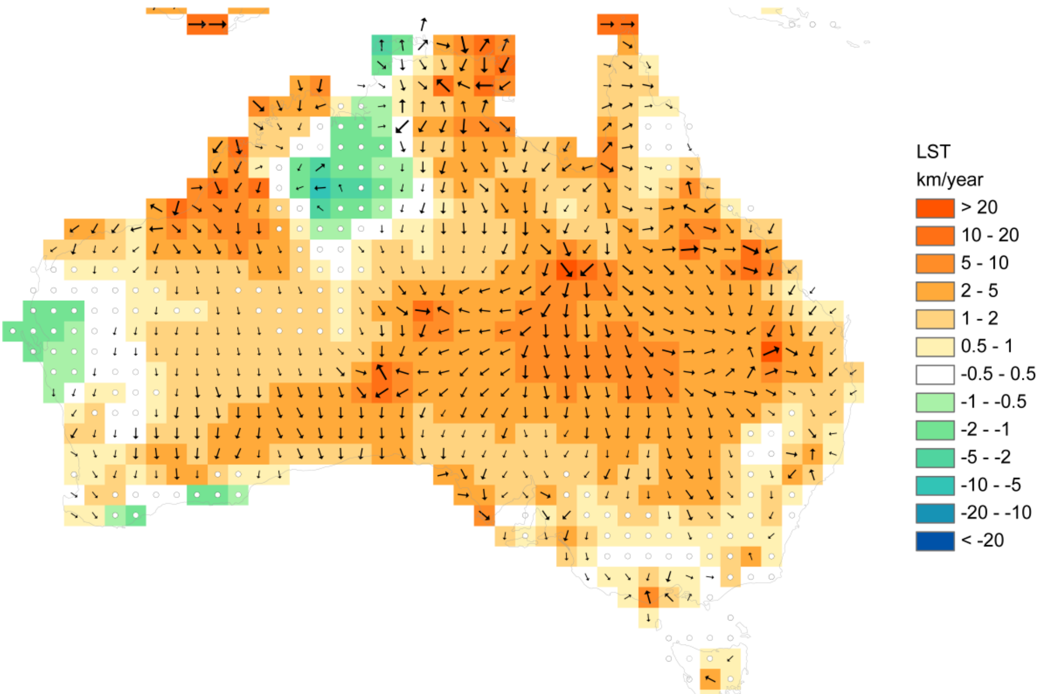

Figure 25: Regional patterns in velocity of land surface temperature (LST) shifts over 50 years (1960–2009). Velocity of isothermal climate change (km/year) was calculated as the ratio of the long-term temperature trend (ºC/year) to the two-dimensional spatial gradient in temperature (ºC/km, calculated over a 3º by 3º grid), oriented along the spatial gradient over 50 years (1960–2009). Source: Burrows *et al.* (Burrows *et al.* 2011), courtesy E. Poloczanska.

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