Queensland's biodiversity under climate change: an overview of climate change in Queensland

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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 gases 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 CO₂ 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 (CO₂) and sulphur dioxide (SO₂) grew 10-fold (WMO 2011).

The concentration of CO₂ 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 CO₂ varies within each year as a result of the annual seasonal cycles of photosynthesis and oxidation (Figure 1).

Of the other greenhouse gases, methane (CH₄)—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 (N₂O) 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/m²); CO₂ contributed some 60 per cent of this figure and CH₄ about 25 per cent, with N₂O 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 CO₂ 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 CO₂ 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 CO₂ (Bindoff et al. 2007).

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 (Masié & 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 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.
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.

![Global average temperature anomalies](http://www.metoffice.gov.uk/hadobs/hadcrut3/diagnostics/global/inh+sh/)

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/inh+sh/](http://www.metoffice.gov.uk/hadobs/hadcrut3/diagnostics/global/inh+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.

Figure 6: Southern Hemisphere 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.
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).
Figure 9: Queensland annual minimum 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 10: Queensland Spring mean temperature anomalies (1950-2010) 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 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/](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](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).

PROJECTED CLIMATE TRENDS

As indicated above, human–mediated emissions of greenhouse gases, dominated by carbon dioxide (CO₂), 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 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).
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 southeast 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 CO₂ concentration (Friedlingstein et al. 2010) (see Bustamante et al. 2012; Murphy 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).
- 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).
- 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 (°C/year) to the seasonal rate of change in temperature (°C/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 (°C/year) to the seasonal rate of change in temperature (°C/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 (°C/year) to the two-dimensional spatial gradient in temperature (°C/km, calculated over a 3° by 3° 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 (°C/year) to the seasonal rate of change in temperature (°C/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 (°C/year) to the seasonal rate of change in temperature (°C/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 (°C/year) to the two-dimensional spatial gradient in temperature (°C/km, calculated over a 3° by 3° grid), oriented along the spatial gradient over 50 years (1960–2009). Source: Burrows et al. (Burrows et al. 2011), courtesy E. Poloczanska.
REFERENCES


Blackford J, Turley C, Widdicombe S, Orr J, Gattuso J-P (2007) 'Ocean Acidification - the other half of the CO2 problem (Fact Sheet No. 7).' (Eur-Oceans Knowledge Transfer Unit, Plymouth Marine Laboratory: Plymouth, UK)


CSIRO, BOM (2007b) 'Climate change in Australia: observed changes and projections.' (CSIRO and Bureau of Meteorology: Melbourne, Australia) 8


Gifford RM (Ed.) (2005) 'Pan evaporation: an example of the detection and attribution of trends in climate variable. Proceedings of a workshop held at the Shine Dome, Australian Academy of Science, Canberra 22-23 November 2004' (National Committee for Earth System Science, Australian Academy of Science: Canberra)


Hardy T, Mason LB, Astorquia A (2004) 'Queensland climate change and community vulnerability to tropical cyclones: Oceans hazards assessment — Stage 3.' (Marine Modelling Unit Report to Australian Bureau of Meteorology and Queensland EPA, School of Engineering James Cook University: Townsville, Queensland) 56


QCCCE (2011) 'Queensland coastal processes and climate change.' (Queensland Climate Change Centre of Excellence, Department of Environment and Resource Management, Queensland Government: Brisbane) 49


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