Climate Change Projections for the Townsville Region

Kevin Hennessy, Leanne Webb,
James Ricketts and Ian Macadam

July 2008

A report prepared for Townsville City Council

www.csiro.au

Enquiries should be addressed to:

Kevin Hennessy
CSIRO Marine & Atmospheric Research
PMB 1
Aspendale, Vic, 3195
Ph +61 3 9239 4536
Kevin.Hennessy@csiro.au

Copyright and Disclaimer

Important Disclaimer

Contact Us
Phone: 1300 363 400
+61 3 9545 2176
Email: enquiries@csiro.au
Web: www.csiro.au

CONTENTS

EXECUTIVE SUMMARY

This report describes climate change projections for the Townsville region. Most material has been generated specifically for this project. Some material has been drawn from a recent assessment of climate change for the whole of Australia (CSIRO and Australian Bureau of Meteorology, 2007).

Summary of estimated future changes in climate for the Townsville region
Temperature
A warming of 0.8°C (with a range of uncertainty of 0.6 to 1.2°C) is likely[1] by 2030, rising to 1.4°C (0.9 to 2.0°C) by 2070 under a low emission scenario, and 2.7°C (1.8 to 3.8°C) for a high scenario. It is extremely likely[2] that the frequency of hot days will increase. Sea surface temperatures are likely to increase 0.7°C (0.4 to 1.1°C) by 2030, rising to 1.2°C (0.6 to 2.0°C) by 2070 under a low emission scenario, and 2.2°C (1 to 3°C) for a high scenario by 2070.
Rainfall, evapotranspiration, humidity and drought
Annual average rainfall is likely to decrease by 2% (-9 to +5%) by 2030, by 4% (-16 to +10%) under a low emission scenario by 2070, and by 8% (-32 to +18%) for a high scenario by 2070. Annual average potential evapotranspiration is likely to increase by 3% (2 to 5%) by 2030, by 6% (4 to 8%) under a low emission scenario by 2070, and by 11% (7 to 16%) for a high scenario by 2070. A slight decrease is likely in the number of rain-days and the intensity of heavy rainfall. Little change in humidity is likely. Droughts are likely to be more frequent and affect larger areas.
Wind-Speed
Annual average wind-speed is likely to increase by 1.3% (0.1 to 2.9%) by 2030, by 2.2% (0.2 to 4.9%) under a low emission scenario by 2070, and by 4.3% (0.3 to 9.4%) for a high scenario by 2070.
Solar radiation
Little change in solar radiation is likely.
Tropical Cyclones and Storm Surges
Little change is likely in the number of cyclone days, but severe cyclones may occur more often. Storm surge heights are likely to increase due to sea level rise and increases in tropical-cyclone intensity.
Fire Weather
The frequency of extreme fire-weather conditions is likely to increase.
Atmospheric Carbon Dioxide
Atmospheric carbon dioxide concentrations are likely to grow from about 390ppm in 2007 to between 429 and 455ppm by 2030 and between 525 and 716ppm by 2070.

[1] "Likely" is greater than 66% probability, consistent with the IPCC (2007) definition
[2] "Extremely likely" is greater than 95% probability, consistent with the IPCC (2007) definition

The changes summarised above should be interpreted as an overview of estimated changes in individual aspects of the climate of the Townsville region. A component of the uncertainty given by the ranges in brackets for some variables is due to different regional responses to global warming in different climate models. As a result, the low and high scenarios of multiple variables *should not be combined* to create “best case” or “worst case” climate change scenarios. Scenarios that are consistent between climate variables should be derived from the output of *individual* climate models. Model-specific scenarios, including information on a limited number of climate variables, can be sourced from the OzClim climate change scenario generator (CSIRO, 2008).

1. INTRODUCTION

The climate change projections presented for the Townsville region in this report are consistent with those published in "Climate Change in Australia", the most up-to-date assessment of climate change for the whole of Australia (CSIRO and Australian Bureau of Meteorology, 2007). Projections for the following climate variables in 2030 and 2070 are given in this report and in an accompanying Excel file (copy provided in the Appendix).

1) Annual and seasonal average temperatures
2) Annual average numbers of hot days
3) Annual and seasonal average rainfall totals
4) Annual and seasonal average evaporation
5) Annual and seasonal average wind-speeds
6) Annual and seasonal average relative humidity
7) Annual and seasonal average solar radiation

Projections in the following climate variables are given in this report but not the Excel files.

1) Annual average number of rain days
2) Heavy rainfall intensity
3) Annual average sea surface temperatures
4) Various properties of tropical cyclones
5) Storm surge heights (for 2050)
6) Drought frequency (for 2030 only)
7) Annual average number of days with extreme forest fire danger (for 2020 and 2050)
8) Atmospheric carbon dioxide concentrations

The projections provide information on climate conditions averaged over several decades in the future. For example, projections provided for 2030 and 2070 reflect average conditions for periods centred on the years 2030 and 2070. The climate of an individual year in the future will be determined by a combination of natural variability and the underlying long-term change due to an intensified greenhouse effect, as illustrated in Figure 1.

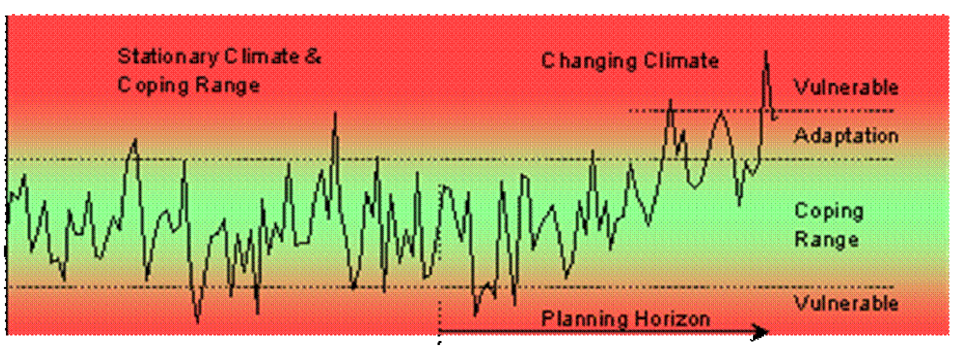

Figure 1: *The vulnerability of a system to changes in the average state of the climate. Source: Jones & Mearns (2005).*

The impact of climate change will often be felt through extreme events. If the coping range of the system is optimised for past climate conditions, then conditions outside the coping range will occur with higher or lower frequency as climate change progresses. Successful adaptation to climate change should alter the coping range in such a way that increases in frequency are minimised. The projections in this report are intended to inform local governments and other decision makers in the Townsville region who may seek to prepare for and adapt to climate change. It is possible that changes in climate variability will also contribute to the vulnerability of systems in the Townsville region. However, there is significant uncertainty about potential changes in variability, which is the subject of ongoing research and is not addressed in this report.

Projected changes in climate variables include ranges of uncertainty. A component of the uncertainty is due to different regional responses to global warming in different climate models. As a result, the low (high) scenarios of several variables *should not be combined* to create best case (worst case) climate change scenarios. This is because since such a combination might not actually be realisable in any individual model. Scenarios that are consistent between climate variables should be derived from the output of *individual* climate models. Model-specific scenarios are critical for detailed risk assessments, for which multiple variables are important. Such scenarios can be sourced from the OzClim climate change scenario generator (CSIRO, 2008). OzClim is designed to provide information about changes in regional monthly-average climate for a range of models and emission scenarios. However, at present, OzClim scenarios include information on only a limited number of climate variables. The utility of the projections presented in this report is in providing an overview of the likely changes in a wide variety of climatic aspects for the Townsville region.

2. OBSERVED CLIMATE CHANGE

2.1 Global Climate Change

In 1988, the United Nations Environment Programme and the World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC). This comprises many of the world's experts on climate change, and produces authoritative reviews of our knowledge of climate change. The most recent review includes a summary describing observed climate change and its causes (IPCC, 2007).

Since the Industrial Revolution, around 1750, the atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased by 35%, 148% and 18%, respectively. The increases in concentrations of carbon dioxide are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture.

The Earth's average surface temperature has increased by approximately 0.7˚C since the beginning of the 20th Century. Most of the warming since 1950 is very likely due to increases in atmospheric greenhouse gas concentrations due to human activities. The warming has been associated with more heatwaves, changes in precipitation patterns, reductions in sea ice extent and rising sea levels.

2.2 Climate Change in Australia

Australian-average annual temperatures have increased by 0.9ºC since 1910. Most of this warming has occurred since 1950 (Figure 2), with greatest warming in the east and least warming in the north-west (Figure 3). The warmest year on record is 2005, but 2007 was the warmest year for southern Australia (Australian Bureau of Meteorology, 2008c). The number of hot days and nights has increased and the number of cold days and nights has declined (CSIRO and Australian Bureau of Meteorology, 2007).

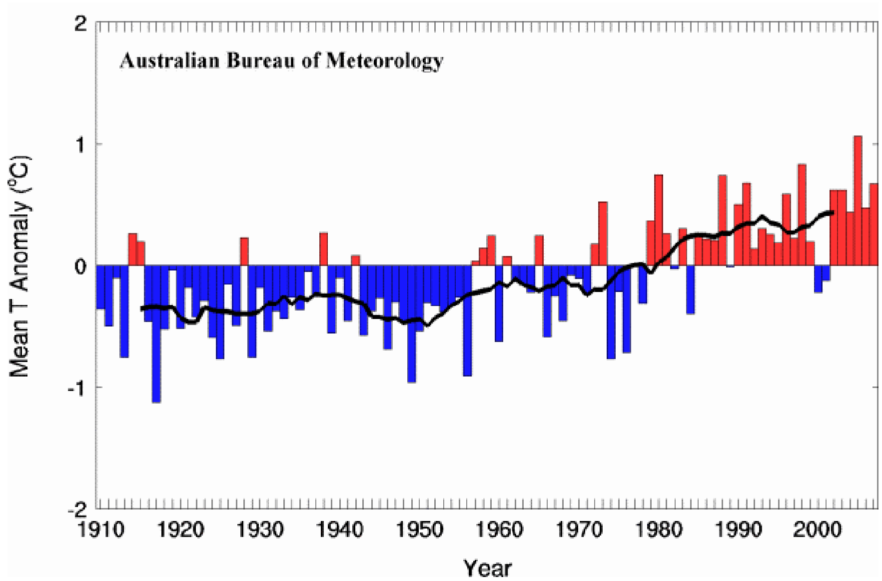

Figure 2: *Australian-average annual temperature anomalies relative to the average for the 1961-1990 period. Source: Australian Bureau of Meteorology (2008a).*

Since 1950, most of eastern and south-western Australia has become drier (Figure 3). Across New South Wales and Queensland rainfall trends partly reflect a very wet period around the 1950s, though recent years have been unusually dry. In contrast, north-western Australia has become wetter over this period, mostly during summer. Since 1950, very heavy rainfall (over 30 mm/day) and the number of wet days (at least 1 mm/day) have decreased in the south and east but increased in the north (Figure 4) (CSIRO and Australian Bureau of Meteorology, 2007).

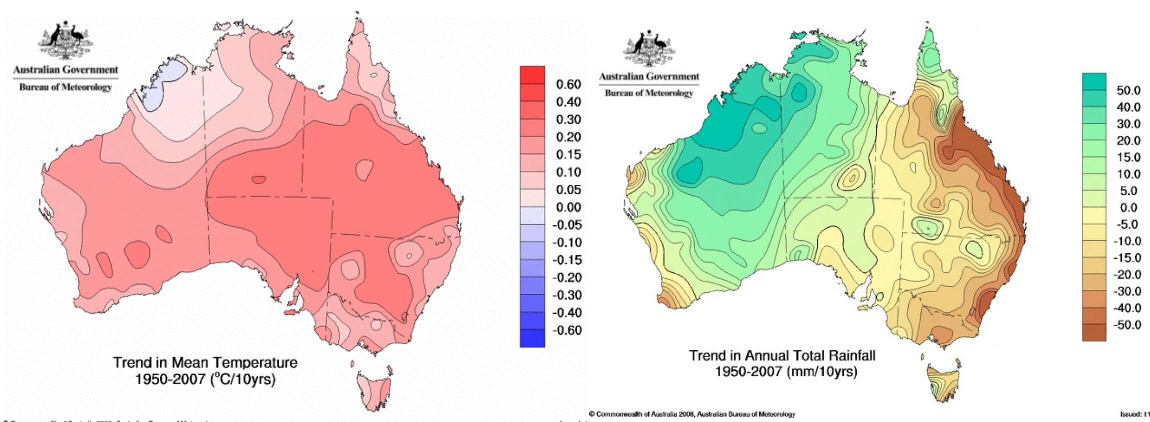

Figure 3: *Trends in annual mean temperature and rainfall since 1950. Source: Australian Bureau of Meteorology (2008a).*

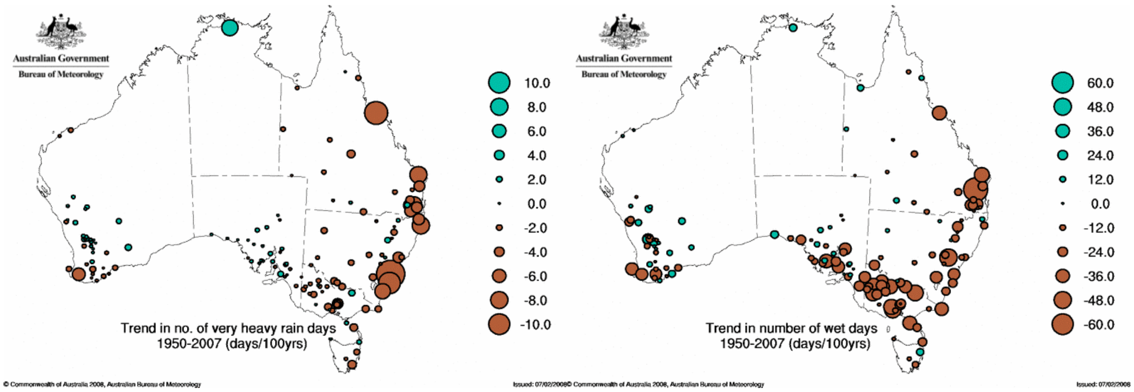

Figure 4: *Trends in the frequencies of very heavy rain days (over 30 mm/day) and wet days (at least 1 mm/day) since 1950. Source: Australian Bureau of Meteorology (2008a).*

Australian rainfall shows considerable variability from year-to-year, partly in association with the El Niño – Southern Oscillation (ENSO). El Niño events tend to be associated with hot and dry years in Australia, and La Niña events tend to be associated with mild and wet years (Power et al. 2006). There has been a marked increase in the frequency of El Niño events and a decrease in La Niña events since the mid-1970s (Power and Smith 2007). The frequency of tropical cyclones in the Australian region has decreased in recent decades, largely due to the increasing frequency of El Niños. However, the number of severe cyclones has not declined (Figure 5).

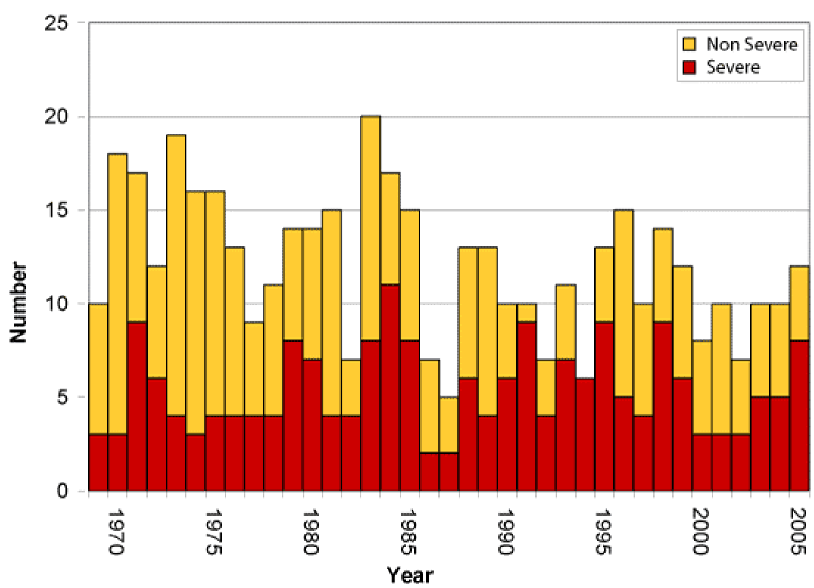

Figure 5: *Annual numbers of severe (minimum central pressure less than 970hPa) and non-severe tropical cyclones in the Australian region. Source: Australian Bureau of Meteorology (2008b).*

3. CLIMATE CHANGE PROJECTIONS

3.1 Method

The future climate is strongly influenced by inherently uncertain factors and for this reason it is not possible to make definitive future climate predictions for decades ahead. However, projections of future climate that account for uncertainties can be made. The distinction between predictions and projections is important for correctly interpreting climate change information.

This report presents projections of average temperatures, rainfall, evaporation, wind-speed, relative humidity, solar radiation and sea surface temperatures for 2030 and 2070 as changes relative to averages for the 1980-1999 period. The projections are consistent with the most up-to-date assessment of climate change in Australia by CSIRO and the Australian Bureau of Meteorology (2007). They were derived from the output of the most recent generation of climate models, which are mathematical representations of the climate system. These are the best tools for estimating future climate (Watterson (2008). Three main sources of uncertainty are accounted for:

1) uncertainty in the future evolution of greenhouse gas and sulphate aerosol emissions;
2) uncertainty in how much the global average surface temperature will respond to increases in atmospheric greenhouse gas concentrations and changes in sulphate aerosol emissions;
3) uncertainty in the regional climatic response to an increase in global average surface temperature.

The first uncertainty is addressed by considering six different scenarios for the future evolution of greenhouse gas and sulphate aerosol emissions described by the IPCC's Special Report on Emissions Scenarios (SRES) (Nakićenović & Swart, 2000). Each of these SRES scenarios, denoted A1B, A1FI, A1T, A2, B1 and B2, is based on a plausible storyline of future global demographic, economic and technological change in the 21st Century. The second uncertainty is addressed by considering the range of global average warming for different emissions scenarios from 23 climate models (Meehl et al. 2007b). The third uncertainty is addressed through detailed analysis of climate model simulations in the Australian region. The output of 23 models is used to derive projections for average temperatures and rainfall totals, the output of 19 models is used for projections for average wind-speed, the output of 14 models is used for average evaporation and relative humidity, 20 models are used for average solar radiation and 12 for average sea surface temperatures (CSIRO and Australian Bureau of Meteorology, 2007). Each model is given a score based on its ability to simulate average patterns of temperature, rainfall and mean sea level pressure in the Australian regions for the period 1961-1990. Models with higher scores are given greater emphasis in the projections.

The uncertainty in regional projections is represented by a probability distribution. These distributions are used to derive the ranges of uncertainty and central estimates (CSIRO and Australian Bureau of Meteorology, 2007). The lowest and highest 10% of the range of model results (10th and 90th percentiles) define the ranges of uncertainty while the median (50th percentile) provides central estimates.

Changes in the climate of Australia by 2030 do not vary greatly from one emission scenario to another. Therefore, a mid-range emission scenario for 2030, called A1B, is used in this report. However, changes by 2070 are heavily dependent on the emission scenario, because the scenarios are highly divergent beyond 2030. Hence changes for 2070 are presented for a "low" and a "high" emission scenario, called B1 and A1FI respectively. Global carbon dioxide emissions from fossil-fuel burning and industrial processes since 2000 are consistent with the A1FI emission scenario (Raupach et al. 2007). Therefore, the A1FI scenario is considered more likely than the B1 scenario in future.

3.2 Temperature

By 2030, annual average temperatures are likely to increase in the Townville region by 0.8°C (with an uncertainty range of 0.6 to 1.2°C). This provides an estimate of the 10-90% range of possibilities. Hence values smaller and higher outside this range cannot be excluded. Warming is likely to be greatest in autumn and summer. By 2070, the average annual temperature could increase by 1.4°C (0.9 to 2.0°C) under a low emission (B1) scenario or by 2.7°C (1.8 to 3.8°C) under a high emission (A1FI) scenario.

The number of hot days is extremely likely to increase. Estimates of the annual average number of extremely hot days were derived by applying projected changes in seasonal-average daily maximum temperatures to observed daily maximum temperatures for the period 1971-2000. In Townsville during this period, the temperature reached 30ºC on about 40% of the days of each year, on average (Table 1). By 2030, 30ºC could be reached on around 50% of days. By 2070, 30ºC could be reached on 50 to 60% of days under a low emission scenario and 60 to 80% of days under a high emission scenario. There were, on average, 4 days per year with temperatures over 35ºC in Townsville during the 1971-2000 period. By 2030, the increase in the annual average number of days with temperatures above 35ºC is around 3 days (2 to 5 days). By 2070, the increase is 8 days (3 to 16 days) under a low emission scenario and 34 days (14 to 82 days) under a high emission scenario. Townsville experienced only 7 days with temperatures over 40ºC in the entire 1971-2000 period. By 2070, an average of 1 or 2 days per year with temperatures over 40ºC could be the norm.

Table 1: *Annual average numbers of days with temperatures over 30°C, 35°C and 40°C at Townsville for the 1971-2000 period, for 2030 for the A1B SRES emissions scenario, and for 2070 for the B1 and A1FI SRES emissions scenarios. Numbers inside brackets indicate ranges of uncertainty.*

	1971-2000	2030	2070	
		A1B	**B1**	**A1FI**
>30°C	150	186 (173-197)	205 (188-227)	256 (222-293)
>35°C	4	7 (6-9)	12 (7-20)	38 (18-86)
>40°C	0	0 (0-1)	1 (1-1)	1 (1-2)

3.3 Rainfall

Some climate models indicate future decreases in rainfall for Townsville while others indicate future increases. However, decreases are more likely than increases (CSIRO and Australian Bureau of Meteorology, 2007). Percentage decreases are likely to be greatest in autumn and spring. Changes in annual average rainfall are likely to be -2% (-10 to +6 %) by 2030 (Table 2). By 2070, changes in annual average rainfall are likely to be -4% (-16 to +10%) under a low emission scenario or -8% (-32 to +18%) under a high emission scenario.

Daily variability of rainfall may change as well as the total quantity of rain falling in a year or season. Slightly fewer rain-days are likely. By 2030, the simulated change in the annual average number of rain days (days with at least 1 mm of rain) is -1% (-5 to +2%). By 2070, the likely change is -1% (-9 to +4%) under a low emission scenario or -3% (-17 to +7%) under a high emission scenario. The intensity of heavy daily rainfall is also likely to decrease slightly. However, projections of heavy rainfall (defined as the heaviest 1% of 24-hour rainfall) are highly uncertain. By 2030, the range of uncertainty is -9 to +6%. For 2070, the range of uncertainty is -16 to +10% under a low emissions scenario or -30 to +20% under a high emissions scenario.

Table 2: *Percentage changes in annual rainfall totals, annual average numbers of rain days and the intensity of rainfall on the heaviest 1% of days for the Townsville region for 2030 for the A1B SRES emissions scenario and for 2070 for the B1 and A1FI SRES emissions scenarios. Numbers inside brackets indicate ranges of uncertainty.*

	2030	2070	
	A1B	**B1**	**A1FI**
Rainfall total	-2 (-10 to +6)	-4 (-16 to +10)	-8 (-32 to +18)
Rain days	-1 (-5 to +2)	-1 (-9 to +4)	-3 (-17 to +7)
Rainfall intensity	0 (-9 to +6)	0 (-16 to +10)	+1 (-30 to +20)

3.4 Evapotranspiration, Wind-Speed, Relative Humidity and Solar Radiation

Evapotranspiration is the combination of evaporation of water from the Earth's surface and transpiration from vegetation. It is a key driver of the hydrological cycle and greatly affects the quantity of water on the surface and in the soil. Potential evapotranspiration is that which would occur if the surface was saturated, and thus gives a measure of maximum possible evapotranspiration under those conditions. Annual average potential evapotranspiration is likely to increase in Townsville by 3% (2 to 5%) by 2030, with the largest percentage increases expected in autumn. By 2070, annual average potential evapotranspiration could increase by 6% (4 to 8%) under a low emission scenario or by 11% (7 to 16%) under a high emission scenario.

Annual average wind-speed near Townsville is likely to increase by 1.3% (0.1 to 2.9%) by 2030, the greatest percentage increases being in winter and spring. By 2070, annual average wind-speed could increase by 2.2 (0.2 to 4.9%) under a low emission scenario or by 4.3% (0.3 to 9.4%) under a high emission scenario.

Relative humidity is a measure of the air's ability to hold moisture. It is the ratio of the amount of water in the air to the maximum amount of water that could be absorbed by the air given an unlimited supply of water. A low value of relative humidity indicates that there is little water in the air relative to its capacity to hold moisture while a high value indicates that the air is saturated with water. Projections of relative humidity show little change in the Townsville region.

Solar radiation is essentially sunshine. Projections of solar radiation show little change in the Townsville region.

3.5 Sea Surface Temperatures

Increases in sea surface temperature can enhance the formation of tropical cyclones and the bleaching of coral reefs. Sea surface temperature projections around Australia for 2030 are shown in Figure 6 for the mid-range A1B emission scenario. The warming near Townsville in 2030 is 0.76°C (0.45 to 0.96°C). By 2070, the warming is 1.12°C (0.76 to 1.60°C) under a low emission scenario or 2.17°C (1.46 to 3.10°C) under a high emission scenario.

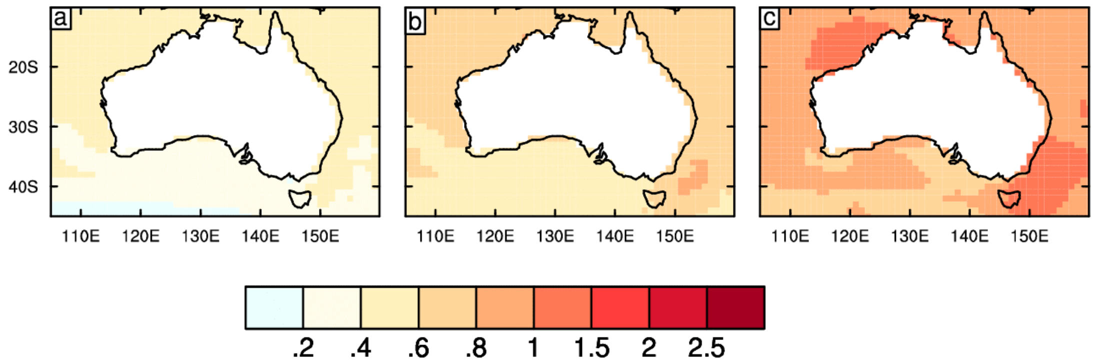

Figure 6: *Changes in annual average sea surface temperature (°C), relative to averages for the 1980-1999 period, around Australia by 2030 for the A1B emission scenario. (a) 10th percentile (b) 50th percentile and (c) 90th percentile. Source: CSIRO and Australian Bureau of Meteorology (2007).*

3.6 Tropical Cyclones

Three recent studies have produced projections for tropical-cyclone changes in the Australian region. Two studies (Walsh et al. 2004 and Leslie et al. 2007) suggest that there will be no significant change in the frequency of tropical cyclones off the east coast of Australia to the middle of the 21st Century. The third study (Abbs et al. 2006) shows reduced frequency off the Queensland coast where cyclones may become more long-lived (Abbs et al. 2006 and Leslie et al. 2007). Southward shifts in the cyclone genesis region of 70km by 2070 (Abbs et al. 2006) and 200km by 2050 (Leslie et al. 2007) are simulated. The combined effect of changes in cyclone frequency, duration and genesis region determines the annual average number of cyclone days (defined as days on which a cyclone resides in a 200 km x 200 km box) for the region (Figure 7). The simulated frequency of severe cyclones (Categories 3 to 5) increases 60% by 2030 and 140% by 2070 (Abbs et al. 2006). Other studies indicate that by 2050, the increase in frequency may be 22% (Leslie et al. 2007) or 56% (Walsh et al. 2004). In summary, for the Townsville region, little change is likely in the annual average number of cyclone days, but severe cyclones may occur more often.

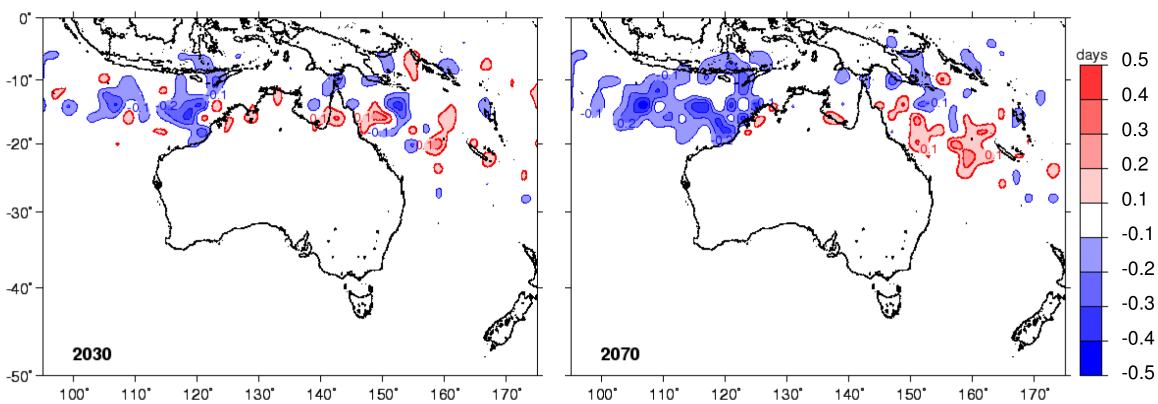

Figure 7: *Changes in annual average numbers of tropical-cyclone days in the Australian region, relative to averages for a 40-year period centred on 1980, for 40-year periods centred on 2030 and 2070. Blue regions indicate a decrease in cyclone occurrence and red regions indicate an increase in occurrence. Source: Abbs et al. (2006).*

3.7 Storm Surges

Mean sea level rise due to global warming occurs as a result of two main processes - the melting of land-based ice, which increases the height of the ocean, and a decrease in ocean density, which increases the volume and hence the height of the ocean. Increases in ocean density in most parts of the world, including Australia, occur largely due to ocean warming rather than reductions in salinity and so the density change component is often referred to as thermal expansion. The amount of thermal expansion is non-uniform due to the influence of ocean currents and spatial variations in ocean warming. From 1961-2003, the rate of sea level rise was globally 1.8 mm per year, with a rise of 3 mm per year from 1993-2003. This rate of increase is ten times faster than the average rate of rise over the previous several thousand years. Around Australia the rate of sea level rise was about 1.2 mm per year during the 20th century (Church and White, 2006). A recent study (Horton et al., 2008) based on IPCC (2007) estimates of global warming found that the range of sea level rise is likely to be 0.13 to 0.20 m by 2030 and 0.32 to 0.56 m by 2070. Higher values cannot be excluded (IPCC, 2007).

The effect of rising mean sea levels will be felt most profoundly during tropical cyclones and extreme storms, when strong winds and falling atmospheric pressure create a temporary and localised increase in sea level known as a storm surge. Higher mean sea levels will enable inundation and waves resulting from storm surges to penetrate further inland, increasing flooding, erosion and damage to infrastructure and natural ecosystems. Future changes in the intensity of tropical cyclones and extreme storms will result in changes in the frequency of storm surges of a given height above mean sea level.

Storm surge projections are not available for Townsville but are available for Cairns (McInnes et al. 2003). Using the historical record of tropical cyclones in the region, probability distributions were developed for cyclone speed, direction of approach and intensity. The cyclone intensity distribution was increased by 10% to represent enhanced greenhouse conditions in 2050 (Walsh and Ryan 2000), although this is smaller than the increases suggested by the studies discussed in Section 3.6. A population of cyclones and coincident tides was randomly selected for the current climate and the 2050 climate, then simulated with a coastal ocean model at 200m resolution. Results show that increasing cyclone intensity by 2050 could increase the height of the 1-in-100 year storm tide (the 1-in-100 year combined height of a storm surge and a tide) by 0.3m (Figure 8a). Projected sea-level rise would enhance this figure. Equivalently, by 2050 the current 1-in-100 year storm surge height may occur, on average, once every 60 years, or once every 40 years if mean sea level rise is accounted for. The areal extent of flooding as a result of the most extreme storm tides increases from approximately 32km^2 to 71km^2 to encompass much of downtown Cairns (Figure 8b).

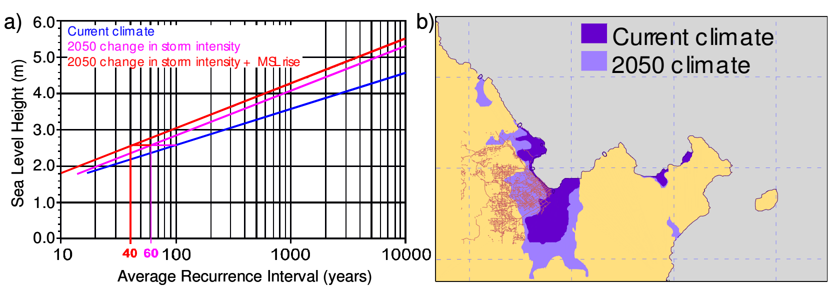

Figure 8: *(a) Return period curves for storm surge height at Cairns, for the current climate (blue), assuming a 10% increase in cyclone intensity (pink) plus mean sea level rise (red). (b) The inundation produced by the most extreme 5% of simulated storm tides (100-year return period and greater) under current climate conditions and conditions assuming a 10% increase in tropical-cyclone intensity by 2050. The road network of Cairns is shown in red to highlight the urban impact of the inundation. Source: McInnes et al. (2003).*

The Cairns results illustrate the possible effects of mean sea level rise and an assumed 10% increase in tropical-cyclone intensity on storm surges along a small section of the coast of tropical Queensland. The height of storm surges is strongly influenced by local bathymetry (shape of the sea floor). Future changes in storm surge heights for Townsville will therefore be of a different magnitude to changes for Cairns. However, it is very likely that Townsville will experience increases in storm tide height due to mean sea level rise and increases in tropical-cyclone intensity.

3.8 Drought

A drought index based on rainfall deficiency alone would fail to account for the effect of projected increases in evaporation. Soil moisture includes the effects of rainfall and evaporation. A recent assessment of projected changes in drought (Hennessy et al., 2008), based on results from 13 climate models, considered changes in exceptionally low soil moisture years over Queensland (occurring once every 16.5 years, on average, over the past 50 years). By the year 2030, these exceptionally low soil moisture years were simulated to occur once every 12.6 years, on average (range of uncertainty 9.3 to 19.4 years). The areal extent of Queensland affected by exceptionally low soil moisture was simulated to be 6.5% over the past 50 years, increasing to 7.4% by 2030 (uncertainty range 4.4 to 10.6%).

3.9 Fire Weather

Fire risk is influenced by a number of factors, including fuel, terrain, land management, fire suppression and weather. The Forest Fire Danger Index (FFDI) is used operationally to provide an indication of fire risk based on four relevant meteorological variables, daily maximum temperature, daily total precipitation, 3 pm relative humidity and 3 pm wind-speed. The FFDI has five intensity categories: low (index value of less than 5), moderate (5-12), high (13-25), very high (25-49) and extreme (at least 50). When the FFDI is extreme, a Total Fire Ban Day is usually declared.

Lucas et al. (2007) generated fire danger projections for 2020 and 2050 for southern and eastern Australia using two climate change simulations of CSIRO's Cubic Conformal Atmospheric Model (CCAM), which has 50km resolution over Australia (McGregor, 2005). One simulation, denoted "CCAM Mark2", was driven by boundary conditions from the CSIRO Mark2 coupled ocean-atmosphere model, while the other simulation, denoted "CCAM Mark3", was driven by boundary conditions from the CSIRO Mark3.0 model. Data from these simulations were then used to generate changes in the relevant meteorological variables per °C of global warming, including changes in daily weather variability. These changes were multiplied by global warming values consistent with the IPCC's Fourth Assessment Report (Meehl et al. 2007b) for 2020 and 2050 and then applied to the daily weather records for the 1974-2007 period for 26 sites in southern and eastern Australia. FFDI values were then calculated for the modified datasets.

An increase in fire risk was indicated at most of the 26 sites. By 2020, the frequency of extreme fire danger days generally increases by 5-25% for a low global warming scenario and by 15-65% for a high global warming scenario. By 2050, the increases are generally 10-50% for a low global warming scenario and 100-300% for a high global warming scenario. The fire season is likely to become longer, starting earlier in the year. Results are not available for Townsville but the closest site studied is Rockhampton (Table 3), where increases in the frequency of extreme fire danger days are 5-30% by 2020, and 5-140% by 2050. These percentage changes are relative to very small baseline frequencies.

Table 3: *Annual average numbers of extreme fire danger days at Rockhampton for present (1973-2007) conditions and conditions in 2020 and 2050 for low and high global warming scenarios. CCAM Mark2 results are denoted "mk2" and CCAM Mark3 results are denoted "mk3".*

1974 to 2007	2020				2050			
	Low mk2	Low mk3	High mk2	High mk3	Low mk2	Low mk3	High mk2	High mk3
0.6	0.6	0.7	0.7	0.8	0.6	0.7	1.2	1.5

3.10 Atmospheric Carbon Dioxide Concentrations

In the half-million years prior to the Industrial Revolution, around 1750AD, atmospheric carbon dioxide concentrations varied between about 180 and 280 parts per million (ppm). Since 1750AD, concentrations have risen by 35%. In 2007, the concentration approached 390ppm. The average growth rate in carbon dioxide concentrations in the 1990s was 1.3% per year but for the period 2000-2006 it was 3.3% per year (Canadell et al. 2007). It is currently tracking the highest IPCC emissions growth scenario (Rahmstorf et al. 2007). The concentration is likely to be between 429 and 455ppm by 2030 and between 525 and 716ppm by 2070 (IPCC, 2007).

4. RECOMMENDATIONS

The projected changes in the climate of the Townsville region described in this report should be interpreted as an overview. They have a number of limitations, which could be mitigated through further work.

In-depth assessments of key impacts of climate change in the Townsville region, on water availability and quality, coastal infrastructure and forest fires, would be facilitated by further studies focussing on the region. Specifically, these should address:

1) implications of projected changes in rainfall and potential evapotranspiration on runoff in the region's drainage basins;

2) effects of mean sea level rise and increases in tropical-cyclone intensity on storm surge heights and coastal inundation;

3) extension of the work of Lucas et al. (2007) on the impacts of climate change on fire weather to the Townsville region.

The climate change projections presented in this report have been designed to sample the uncertainty in the response of regional climate conditions to global warming. The extent to which this has been achieved for an individual climate variable is dependent on the number of climate models used in the analysis. Key parts of the analyses of future changes in hot days, rain days, heavy rainfall intensity, tropical cyclones, storm surges and fire weather are based on a small number of climate models. This means that the uncertainty has been poorly sampled, so results beyond those presented may be possible. Further work that makes use of the output of a larger set of climate models would facilitate better estimation of uncertainty in these changes. The availability of output from the models on a daily time scale would be critical to such work and each model should be tested for its ability to reproduce relevant aspects of the current climate of Australia at a fine spatial scale.

At present, OzClim scenarios (CSIRO, 2008) include information for only a small number of climate variables from a limited number of climate models. Further work could provide scenarios comprising a consistent set of changes in more of the climate variables of interest. These would be suitable as input for in-depth assessments of the impact of climate change on systems for which multiple climate variables are important. Such a set of projections would rely on a common set of climate models being used to derive changes in all of the climate variables of interest. The set of models would either need to be large or carefully selected to properly sample the uncertainty in the response of regional climate conditions to global warming.

Information about future changes in interannual climate variability is essential for some types of climate risk assessment. Such information is not included in this report and is not available from OzClim. However, CSIRO and the Australian Bureau of Meteorology are proposing the development of a web-based tool for providing time series of regional climate data for a range of climate variables from a selection of climate models. This would provide information on changes in interannual climate variability and it may be prudent to revisit climate change projections for the Townsville region in the light of output from such a tool.

ACKNOWLEDGMENTS

We acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, US Government Department of Energy.

The work of the authors also draws upon research findings of many colleagues within CSIRO Marine and Atmospheric Research and overseas research institutions. CSIRO climate models were developed by members of CSIRO Marine and Atmospheric Research.

Comments from Dr Scott Power (Bureau of Meteorology) were very useful.

REFERENCES

Abbs, D.J., S. Aryal, E. Campbell, J. McGregor, K. Nguyen, M. Palmer, T. Rafter, I. Watterson and B. Bates, 2006: *Projections of Extreme Rainfall and Cyclones.* A report to the Australian Greenhouse Office, Canberra, Australia, 97 pp.

Australian Bureau of Meteorology, 2008a: *Australian Climate Change and Variability.* Australian Bureau of Meteorology website, http://www.bom.gov.au/cgi-bin/silo/products/cli_chg/.

Australian Bureau of Meteorology, 2008b: *Tropical cyclone trends.* Australian Bureau of Meteorology website, http://www.bom.gov.au/weather/cyclone/tc-trends.shtml.

Australian Bureau of Meteorology, 2008c: *Annual Climate Summary 2007.* http://www.bom.gov.au/climate/annual_sum/2007/

Canadell, J.G., C. Le Que´re´, M.R. Raupach, C.B. Field, E.T. Buitenhuis, P. Ciais, T.J. Conway, N.P. Gillett, R.A. Houghton and G. Marland, 2007: Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the USA*, **104**, 18866–18870.

Church, J.A. and N.J. White, 2006: 20th century acceleration in sea-level rise. *Geophysical Research Letters*, **33**, L01602

CSIRO and Australian Bureau of Meteorology, 2007: *Climate Change in Australia*. Technical report, 140 pp, http://www.climatechangeinaustralia.com.au/resources.php.

CSIRO, 2008: *OzClim.* CSIRO website, http://www.csiro.au/ozclim/home.do.

Hennessy, K.J., Fawcett, R., Kirono, D., Mpelasoka, F., Jones, D., Bathols, J., Whetton, P., Stafford Smith, M., Howden, M., Mitchell, C. and N. Plummer, 2008: *An assessment of the impact of climate change on the nature and frequency of exceptional climatic events*. CSIRO and the Australian Bureau of Meteorology, 31 pp. http://www.bom.gov.au/climate/droughtec/

Horton, R., C. Herweijer, C. Rosenzweig, J.P. Liu, V. Gornitz, and A.C. Ruane, 2008: Sea level rise projections for current generation CGCMs based on the semi-empirical method. *Geophys. Res. Lett.,* **35**, L02715, doi:10.1029/2007GL032486.

IPCC, 2007: *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones, R. N., and L. O. Mearns, 2005: *Assessing Future Climate Risks. In: Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures* [Lim, B., E. Spanger-Siegfried, I. Burton, E. Malone and S. Huq (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 119-144.

Leslie, L.M., D.J. Karoly, M. Leplastrier and B.W. Buckley, 2007: Variability of tropical cyclones over the southwest Pacific Ocean using a high resolution climate model. *Continuum Mechanics and Thermodynamics*, **19**, Issue 3-4, 133-175.

Lucas, C., K.J. Hennessy, G. Mills and J.M. Bathols, 2007: *Bushfire Weather in Southeast Australia: Recent Trends and Projected Climate Change Impacts.* A report prepared by the Bushfire CRC, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research for The Climate Institute of Australia, 80 pp, http://www.cmar.csiro.au/e-print/open/2007/hennesseykj_c.pdf.

McGregor, J. L., 2005: *C-CAM: Geometric Aspects and Dynamical Formulation*. CSIRO Atmospheric Research Technical Paper No. 70, 43 pp, http://www.cmar.csiro.au/e-print/open/mcgregor_2005a.pdf.

McInnes, K.L., K.J.E. Walsh, G.D. Hubbert and T. Beer, 2003: Impact of sea-level rise and storm surges on a coastal community. *Natural Hazards*, **30**, 187-207.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J.F.B. Mitchell, R.J. Stouffer and K.E. Taylor, 2007a: The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bulletin of the American Meteorological Society*, **88**, 1383–1394.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007b: *Global Climate Projections. In: Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nakićenović, N., and R. Swart (eds.), 2000: *Special Report on Emissions Scenarios*. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599 pp.

Power, S., M. Haylock, R. Colman and X. Wang, 2006: The predictability of interdecadal changes in ENSO activity and ENSO teleconnections. *J. Climate*, **19**, 4755-4771.

Power, S.B., and I.N. Smith, 2007: Weakening of the Walker Circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed? *Geophys. Res. Lett*., **34**, L18702, doi:10.1029/2007GL30854.

Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker and R.C.J. Somerville, 2007: Recent climate observations compared to projections. *Science*, **316**, 709-710.

Raupach, M.R., G. Marland, P. Ciais, C. Le Que´re´, J.G. Canadell, G. Klepper and C.B. Field, 2007: Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the USA*, **104**, 10288–10293.

Walsh, K.J.E., K.C. Nguyen, and J.L. McGregor, 2004: Finer-resolution regional climate model simulations of the impact of climate change on tropical cyclones near Australia. *Climate Dynamics*, **22**, 47-56.

Walsh, K.J.E. and B.F. Ryan, 2000. Tropical cyclone intensity increase near Australia as a result of climate change. *Journal of Climate*, **13**, 3029-3036.

Watterson, I. G., 2008: Calculation of probability density functions for temperature and precipitation change under global warming. *Journal of Geophysical Research*, Doi:10.1029/2007JD009254.

APPENDIX

	season		2030	2030	2030	2070	2070	2070	2070	2070	2070
			A1B	A1B	A1B	B1	B1	B1	A1FI	A1FI	A1FI
site			10	50	90	10	50	90	10	50	90
TOWNSVILLE	ann	mean temp (deg C)	0.6	0.8	1.2	1.0	1.4	1.9	1.9	2.7	3.7
TOWNSVILLE	djf		0.6	0.8	1.2	0.9	1.4	2.0	1.8	2.7	3.9
TOWNSVILLE	mam		0.6	0.8	1.2	0.9	1.4	2.0	1.8	2.7	3.9
TOWNSVILLE	jja		0.6	0.8	1.2	0.9	1.4	2.0	1.8	2.7	3.8
TOWNSVILLE	son		0.6	0.8	1.1	0.9	1.4	1.9	1.8	2.6	3.7
TOWNSVILLE	ann	rain (%)	-9.8	-2.3	5.7	-16.3	-3.9	9.5	-31.6	-7.5	18.4
TOWNSVILLE	djf		-9.9	-1.6	7.8	-16.5	-2.7	12.9	-32.0	-5.3	25.0
TOWNSVILLE	mam		-13.6	-3.3	10.1	-22.6	-5.5	16.9	-43.7	-10.6	32.7
TOWNSVILLE	jja		-13.0	-1.2	12.3	-21.7	-2.1	20.4	-42.0	-4.0	39.5
TOWNSVILLE	son		-16.2	-5.8	7.3	-27.0	-9.7	12.2	-52.2	-18.8	23.5
TOWNSVILLE	ann	min temp (deg C)	0.6	0.9	1.2	1.0	1.4	2.0	1.9	2.7	3.8
TOWNSVILLE	djf		0.6	0.8	1.2	0.9	1.4	2.0	1.8	2.7	3.8
TOWNSVILLE	mam		0.6	0.9	1.2	0.9	1.4	2.0	1.8	2.7	4.0
TOWNSVILLE	jja		0.6	0.9	1.2	1.0	1.5	2.1	1.9	2.8	4.0
TOWNSVILLE	son		0.6	0.8	1.1	0.9	1.4	1.9	1.8	2.6	3.7
TOWNSVILLE	ann	max temp (deg C)	0.6	0.8	1.1	0.9	1.4	1.9	1.8	2.7	3.7
TOWNSVILLE	djf		0.6	0.9	1.2	1.0	1.4	2.0	1.8	2.7	3.9
TOWNSVILLE	mam		0.5	0.8	1.2	0.9	1.4	1.9	1.7	2.6	3.8
TOWNSVILLE	jja		0.5	0.8	1.1	0.9	1.3	1.9	1.8	2.6	3.7
TOWNSVILLE	son		0.6	0.8	1.1	0.9	1.3	1.9	1.8	2.6	3.6
TOWNSVILLE	ann	Potential evap (%)	2.1	3.3	4.9	3.6	5.5	8.2	6.9	10.7	15.8
TOWNSVILLE	djf		1.4	3.2	5.6	2.3	5.4	9.4	4.4	10.4	18.2
TOWNSVILLE	mam		2.4	3.9	5.9	3.9	6.5	9.9	7.6	12.5	19.1
TOWNSVILLE	jja		2.5	3.8	5.6	4.1	6.3	9.3	8.0	12.2	18.0
TOWNSVILLE	son		1.8	2.8	4.2	2.9	4.7	6.9	5.7	9.0	13.4
TOWNSVILLE	ann	Relative Humidity (%)	-0.4	0.0	0.4	-0.7	0.0	0.6	-1.4	0.0	1.2
TOWNSVILLE	djf		-0.8	-0.2	0.4	-1.3	-0.4	0.6	-2.6	-0.7	1.2
TOWNSVILLE	mam		-0.6	0.0	0.7	-1.0	0.1	1.2	-2.0	0.1	2.3
TOWNSVILLE	jja		-0.7	0.1	0.8	-1.1	0.1	1.3	-2.1	0.2	2.5
TOWNSVILLE	son		-0.4	0.0	0.4	-0.7	0.0	0.7	-1.3	0.0	1.4
TOWNSVILLE	ann	Solar Radiation (%)	-1.1	0.1	1.3	-1.9	0.1	2.1	-3.7	0.2	4.1
TOWNSVILLE	djf		-2.0	0.2	2.3	-3.4	0.4	3.8	-6.5	0.8	7.4
TOWNSVILLE	mam		-1.6	0.1	1.8	-2.6	0.2	3.1	-5.0	0.3	5.9
TOWNSVILLE	jja		-1.5	0.0	1.2	-2.5	-0.1	2.0	-4.8	-0.1	3.8
TOWNSVILLE	son		-0.9	0.0	1.0	-1.6	0.0	1.7	-3.0	0.0	3.2
TOWNSVILLE	ann	wind (%)	0.1	1.3	2.9	0.2	2.2	4.9	0.3	4.3	9.4
TOWNSVILLE	djf		-2.2	1.3	4.9	-3.7	2.2	8.1	-7.2	4.3	15.7
TOWNSVILLE	mam		-1.7	0.7	3.4	-2.8	1.2	5.6	-5.5	2.3	10.9
TOWNSVILLE	jja		-0.8	1.6	4.3	-1.3	2.7	7.1	-2.5	5.2	13.7
TOWNSVILLE	son		-0.2	2.0	4.3	-0.4	3.3	7.2	-0.8	6.3	14.0
TOWNSVILLE	ann	extreme rainfall (%)	-9.4	0.2	6.1	-15.7	0.4	10.2	-30.4	0.8	19.7
TOWNSVILLE	ann	rain days	-5.1	-0.8	2.3	-8.5	-1.3	3.8	-16.5	-2.5	7.4