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Temperature and rainfall trends in northern Australia 1911–2013: implications for human activity and regional development

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ABSTRACT: The climates of the earth's tropical regions are already towards the upper end of human thermal tolerance. The northern Australian tropical region is a particularly challenging environment for human physical activity and regional development projects. Increases in temperature and rainfall will exacerbate these challenges. Knowledge of past climatic trends and their impacts provides important information for prudent development planning. This paper quantifies the observed changes in temperature and rainfall across northern Australia for the period 1911–2013, based on Australian Bureau of Meteorology (BOM) temperature and rainfall data for 4 coastal and 3 inland locations across the region. We compared two 30 yr periods, 1911–1940 and 1984–2013, to the baseline period 1961–1990 averages and SD values. Trends were identified in decadal monthly temperatures, maximum temperatures >30°C and minimum temperatures >21°C, shifts in the daily maximum and minimum temperature frequency distribution curves and changes in seasonal rainfall above and below the ±1 SD values. The results indicate this tropical region is now warmer and wetter compared to the 1911–1940 period with an increase in the number of days >30 and >33°C. Coastal warming was more pronounced than at inland locations and shows seasonal variations; whilst western and central inland areas have become wetter, little trend change was apparent in the eastern rainfall. With projections of further warming, development plans for the region need to incorporate the associated deleterious impacts on human activity. Such decisions will be critical in determining the success or failure of these projects.

KEY WORDS: Northern Australia · Temperature · Rainfall · Health · Climate · Development

1. INTRODUCTION

The human species, through evolution, is physiologically well adapted to living in cool and temperate climates (Hanna & Tait 2015). Warmer climates therefore can present considerable difficulties for humans, as excess heat directly impacts on issues of health, work capacity, domestic and social activities (Hanna et al. 2011b).

The climate of tropical northern Australia is at the upper range of human thermal tolerance. Apart from the pleasant conditions in this region during the Dry season (June–August), the high temperatures and humidity from September through May, which peak during the Wet season (January–March), make living and working conditions difficult. These challenges contribute to high population turnover (Hall et al. 2007) and low permanent population numbers throughout the region, along with a considerable decline in Wet season tourist numbers. Many people simply do not want to live in such harsh climatic conditions.

Throughout the 150 yr of European settlement in Australia, many attempts to settle the inland and northern regions of Australia have ended in spectacular failure (Cook 2009). In the absence of meteorological data and climatological understanding, these at-

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tempts relied on farming practices directly imported from northern Europe and spurred by successes in the Americas (Bauer 1977). With the rekindled drive to develop northern Australia as per the 2015 Federal Government 'White Paper on Developing Northern Australia' (Office of the Prime Minister and Cabinet 2015), these salient lessons from repeated past failures (Woinarski et al. 2007) must not be forgotten. Against a backdrop of fiscal constraint, this White Paper pledges billions of dollars for investment; yet, whilst it notes climate is 'an issue', the report steadfastly neglects to address its potential significance. We argue that understanding the inherent risks and adapting to the regional climate is likely to be critical in determining the success of project development.

Coupling past climate data collected over the last 100 yr with a better understanding of Australia's climate drivers and the ability to model future climate scenarios now offers a way to avoid repeating history's past mistakes. Furthermore, recent epidemiological research has greatly improved our knowledge of the impacts of tropical weather conditions on human physiological and mental health (Hanna & Tait 2015).

Combining this new knowledge facilitates optimal policy development to enhance project success and better protect people expected to live and work in the region. This is particularly relevant, as global warming projections indicate further exacerbation of these pre-existing challenges of living in difficult tropical environments.

There is growing concern that present climate change information is often not suitable or has little practical application for end users. This results in polarisation in world views on climate and exclusion of climate risks in planning (Stern 2016). Planners need information relevant to their geographical and temporal scales. In response to these demands, we have analysed actual recorded data from 7 of the more populated city and township localities across northern Australia rather than using gridded data sets that use regionally averaged data. These sites provide good coast-to-coast coverage, including inland locations. This fine-scaled and regional analysis improves the local relevance, and thus utility, of climate trend data and serves to enhance community understanding of the risks for human activity and planning for future societal needs.

This study reports on the first phase of a larger program of work and identifies the overall trends in temperature and rainfall across the region. Further studies will report on the trends in the extreme temperature and rainfall ranges (Phase 2) and detail the implications for human health and activities (Phase 3). In this paper we provide original analysis quantifying the warming trend and rainfall changes across northern Australia over the period 1911–2013 using the standard climate parameters of daily maximum temperature (T_{max}), daily minimum temperature (T_{min}) and monthly rainfall. Humidity was excluded from this analysis, as the data were not available for the early period. Trends are provided for the comparison 30 yr periods for the early century (1911–1940) and late century (1984–2013) based on the 1961–1990 reference period.

Our study region and the 7 locations (Fig. 1) are located north of latitude 20° S, well within the Tropic of Capricorn. It covers an area of nearly 2×10^6 km^2 spanning an east/west distance of 2350 km and a north/south distance up to 900 km.

Despite the fact that this area comprises 25% of the Australian land mass, it is only inhabited by around

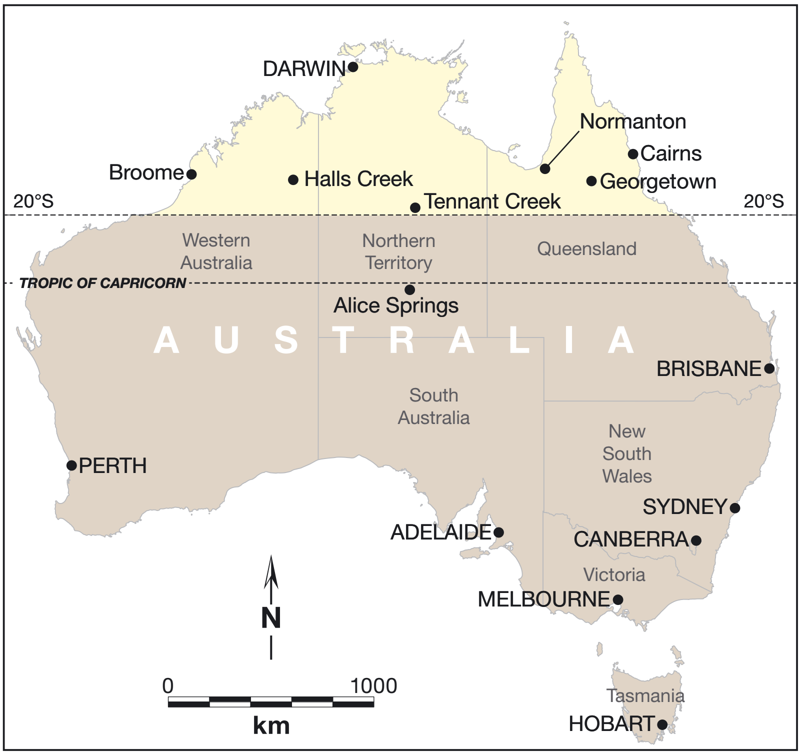

Fig. 1. Study locations in northern Australia (yellow area). © The Australian National University

1 million people, 5% of Australia's population (720 000 in Queensland [QLD]; 230 000 in Northern Territory [NT]; and 50 000 in Western Australia [WA]), many of whom reside in the larger coastal cities of Broome, Darwin, Townsville and Cairns. The Australian Bureau of Statistics (ABS) estimates the total Australian population could double from 22.7 m (2012) to between 36.8 and 48.3 m by 2061, with Queensland increasing from 4.6 m (2012) to between 7.9 and 11.1 m people (ABS 2012). In contrast, the 2015 White Paper estimates a 5-fold increase in the northern Australian population to 5 m people over the next 50 yr. This projection appears to exclude impacts of the climate on liveability in this region.

2. GEOGRAPHY AND CLIMATE OF NORTHERN AUSTRALIA

Australia is the oldest, flattest (ABS 2008a) and driest inhabited continent (Holper 2011) on earth which has lost most of its nutrient-rich topsoils. The Great Dividing Range is a range of mountains that extends along the length of the eastern seaboard, which profoundly influences regional weather and rainfall patterns and land use (ABS 2008b). This range separates the narrow, relatively fertile coastal strip, with its more pleasant coastal climates, from the hotter and drier climates to the west and associated changes to the vegetation and carrying capacity.

Australia not only has the greatest variability of rainfall of any country (Love 2004), but the inter-annual variability of rainfall over northern Australia is considerably greater than other 'Wet–Dry' tropical parts of the world (Petheram et al. 2014). Dorothea Mackellar, in her in 1904 poem 'My Country' (Serle 1949), immortalized this variability by calling Australia a 'land of droughts and flooding rains'.

The annual weather and climate of northern Australia is dominated by 2 broad-scale weather systems; the subtropical ridge (STR) to the south, and the monsoon trough to the north. As these systems move with the sun's annual progression, they produce the alternating Dry (April to September) and Wet seasons (October to March). Approximately 90% of northern Australian annual rainfall occurs during the Wet season (Petheram et al. 2014) along with extreme events such as tropical cyclones, heavy monsoonal rain, thunderstorms and prolonged floods. Because the region lies within the Tropic of Capricorn, the daily and monthly variations in T_{max} are very small compared to southern temperate Australia: the mean monthly annual variation in T_{max} is 6°C in northern Australia compared to 11°C in southern Australia (Hanna & Davis 2015). However, T_{min} can vary considerably between the seasons across the north, especially in inland areas away from oceanic influences.

Australia's climate variability is also driven by the interactions of inter-annual climate drivers such as El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which can generate the rapid swings between dry and wet conditions as identified in Mackellar's poem. Such drivers contribute to extreme flood events and severe protracted droughts such as the Millennium Drought (1996–2010) (BOM National Climate Centre 2010), the most severe drought recorded in Australia.

The combined effects of ENSO, the IOD[1] and the Inter Decadal Pacific Oscillation (IPO) create significant 'background noise' or natural climate variability, whereby large short-term variations can mask small gradual long-term trends. The World Meteorological Organization (WMO) recommends that studies use datasets with a minimum 30 yr timespan in order to filter out this variability and to ensure rigor in long-term trend analyses. This rationale is explained in the *WMO Guide to Climatological Practices* (WMO 2012, p. 100). We have used the Australian Bureau of Meteorology (BOM) standard 30 yr reference period 1961–1990 as the baseline period for this study.

For this analysis, the Dry–Wet annual weather cycle for temperature has been further divided into 5 seasons:

- Transition to Dry season (April–May)
- Dry season (June–August)
- Early Build-up (September–October)
- Late Build-up (November–December)
- Wet season (January–March)

As well as better reflecting the distinctive characteristics of Australia's tropical seasons, this weather cycle also allows for the impacts of ENSO events to be included in the year that they occur. However, as there are large rainfall variations across the year, our rainfall analysis is divided into just 2 seasons: the Wet (October–March) season and the Dry (April–September) season.

Fig. 2 summarizes the annual climate of northern Australia for the selected locations based on the 1961–1990 reference period. This summary indicates that there are 9 mo (coastal) and 8 mo (inland) where

[1] A brief description of these weather and climate influences on Australia can be found at www.bom.gov.au/watl/about-weather-and-climate/australian-climate-influences.shtml

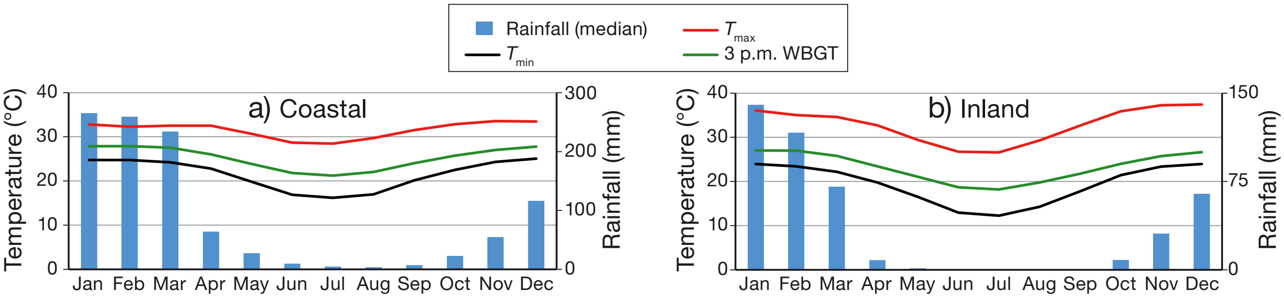

Fig. 2. Climate summaries for (a) coastal and (b) inland locations for northern Australia (1961–1990). T_{min}: daily minimum temperature; T_{max}: daily maximum temperature; 3 p.m. WBGT: wet bulb global temperature at 3 p.m. (15:00 h)

the mean monthly T_{max} is >30°C, and >33°C for 2 mo (coastal) and 6 mo (inland). It also shows that for half the year the mean monthly T_{min} is >21°C (7 mo coastal and 6 mo inland). This summary also highlights the extreme range in rainfall between the Wet and Dry seasons. The 3 p.m. (15:00 h) wet bulb global temperature (WBGT) as calculated from the monthly temperature, relative humidity and wind speed, across these locations is also shown. Developed in the 1950s by the United States military (Budd 2008), the WBGT is the ISO Standard (ISO 7243) index and is designed to indicate the thermal environment influence on human activity and health (ISO 1989). Although not widely used by meteorology services, the WBGT is the industry standard heat stress index for occupational health, the military and international sporting bodies such as the International Association of Athletics Federations (IAAF).

The WBGT provides a sliding scale of risk for varying intensities of work and required work/rest ratios for the acclimatised and non-acclimatised. For example, a WBGT of 27°C would necessitate acclimatised workers undergoing moderate exercise to work no more than 25–50% of a given hour, and rest for the remaining part of that hour. (Here, moderate exercise is defined as 'walking about with moderate lifting and pushing or pulling; walking at moderate pace; e.g. scrubbing in a standing position') (CCOHS 2016). This limitation carries potential to significantly hamper productivity. The average 3 p.m. WBGT for 5 mo of the year is 27°C or more at coastal locations and for 2 mo inland. Site-specific summaries are provided in Supplement 1 at www.int-res.com/articles/suppl/c071p001_supp.pdf. The WBGT used in this study was calculated using the Liljegren method as outlined in Lemke (Lemke & Kjellstrom 2012) for outdoor exposure ($WBGT_o$), and assuming wind speed at 1 m s^{-1}:

$$WBGT_o = 0.7\ T_{nwb} + 0.3\ T_g + 0.1\ T_a$$

where T_{nwb} is natural wet bulb defined as the temperature indicated by a sensor covered with a wetted wick naturally ventilated (Alfano et al. 2012), T_g is globe temperature and T_a is ambient temperature.

3. GEOGRAPHIC AND CLIMATIC CONSTRAINTS ON SETTLEMENT AND DEVELOPMENT

The tropical weather and climate of northern Australia imposes 3 major constraints on development projects in northern Australia: (1) threats from water insecurity, (1) extreme weather events and (3) the debilitating effect and risks to health of the heat and humidity on the people expected to live and work in this region.

The combination of the climate and poor soils reduces much of the continent's capacity to sustain human settlements, limits agricultural activities (Hanna et al. 2011a) and threatens local food production and bush tucker (any food native to Australia and used as sustenance by original inhabitants, the Aboriginal Australians) (Taylor & Tulloch 1985). The extended Dry season, particularly after a poor Wet season, significantly diminishes water supplies and sets limitations for permanent human settlement (Petheram et al. 2014). Many of the rivers in the north flow for <50% of the year. Net evaporation losses (i.e. difference between evaporation and rainfall) during the Dry season can be >50% (Petheram et al. 2014), which restricts capacity to store water for multiple years and leads to major water deficits, and for most species, survival is dependent on maintaining access to water throughout this time.

High ambient heat exposure is a well-known health hazard, which reduces human performance and work capacity (Kjellstrom et al. 2016). The optimal ambient temperatures for peak human physical performance is 11°C, and performance declines sharply when the ambient temperature rises above 21°C (Cuddy et al. 2014). Effective human thermoregulation requires a gradient across the skin in temperature and humidity. When there is little gradient, the rate of loss of the heat produced by moving muscles (exercise) is impeded, resulting in rising core temperatures, which is perceived as uncomfortable and fatiguing, and results in a reduction in physical output capacity (Tucker et al. 2004, Hanna & Tait 2015). Beyond 30°C, this excess heat generated becomes increasingly more difficult to shed to the surrounding environment.

Core body heat gain is also associated with poor physical and mental health outcomes, as well as an increasing the risk of accidents (Tawatsupa et al. 2010). This heat stress leads to a sharp decrease in the physical capacity to work (Srivastava et al. 2000, Altinsoy & Yildirim 2015) or even conduct activities of daily living (Hanna & Tait 2015), and an increase in heat-related death rates (González-Alonso et al. 1999, Sawka et al. 2001, WMO 2013). The IAAF recommends that once the WBGT exceeds 28°C, restrictions to the time spent in outdoor activities must be implemented (IAAF 2012). While the average 3 p.m. WBGT across the region does not reach 28°C, this threshold can be exceeded at individual sites on a regular daily basis over a period of several months.

Globally, heat related deaths are increasing markedly (WMO 2013). Analysis of heat thresholds (mortality response functions) in Australia's capital cities, Adelaide, Perth, Brisbane, Sydney, Melbourne and Hobart are 30, 29, 28, 27, 26 and 26°C, respectively, and 33°C for Darwin (Bambrick et al. 2008). This is the daily maximum temperature above which deaths significantly climb. However, discomfiture and debilitating fatigue occur well before death. People moving to northern Australia from the more populous southern states are very likely to find coping with the heat and humidity of the north extremely difficult, because the temperature is >30°C most of the year.

Night-time temperatures are also relevant to physiological heat shedding and cooling of the housing stock. Analyses of human heat mortality relationships and heat wave definitions include night-time temperatures (Bi et al. 2011, Nairn & Fawcett 2015). Hot nights provide little cooling relief, and while high $T_{\min}$ is strongly associated with mortality, we could find no studies that indicate $T_{\min}$ thresholds above which mortality increases.

The extended period of the year across northern Australia during which there is a combination of high WBGT, $T_{\max}$ and $T_{\min}$, highlights the existing hazardous climatic conditions for human activity. Further warming will intensify these population health risks.

While these conditions are particularly severe in northern and inland regions, and directly contribute to low population densities with few large settlements, the east coast of northern Queensland experiences a somewhat less extreme climate. The combination of agriculture, the tourist attractions of the Great Barrier Reef and tropical rain forests makes this region better able to attract and retain residents. However, far-north coastal Queensland still remains considerably less populated than the more temperate climates of Queensland's more southern coastline.

Extreme weather events during the Wet season pose considerable risks to the long-term viability of any development. Under a changing climate, the severity of tropical cyclones, but not the total number, are projected to increase, especially under the influence of extreme La Niña events (Cai et al. 2015). Such an increase could threaten the viability of agricultural enterprises requiring long-lived plants. For example, the Macadamia nut is endemic to north Queensland, yet 2 Category 5 cyclones (Larry in 2006, Yasi in 2011) within 5 yr devastated this industry by destroying both mature trees and their replantings (Sorensen 2015).

Inter-annual climate drivers, such as ENSO events, bring devastating effects to human health, regional and national economies and the reduction in agricultural yields. These events have had considerable bearing on Australia's worst drought (El Niño) (Holper 2011) and the worst flooding (La Niña) (National Climate Centre 2012) on record.

Recent examples of Australia's climate variability include the 3 yr successive monsoon failure in western Queensland and the Millennium Drought (1996–2010). In western Queensland, the period from October 2012 to December 2015 (BOM 2016) was the worst drought in the region's documented record with severe agricultural (Department of Agriculture and Fisheries 2015) and human health impacts (Dick 2016). The Millennium Drought over southern Australia devastated agricultural yields and commodity export earnings (House of Representatives Standing Committee on Infrastructure Transport Regional Development and Local Government 2009) and exacerbated world hunger by increasing global food prices (Oxfam Australia 2011). This drought also reignited ideas of diversifying Australia's resource base by capitalising on the underutilized northern water resources for agricultural development.

In a dry continent such as Australia, water security is a primary concern. The projected increase in swings between extreme El Niño and La Niña events

(Cai et al. 2015) could therefore jeopardize Australia's economic future and wellbeing. The impact of climate change on Australia's already highly variable rainfall patterns should thus be driving major planning decisions.

4. MATERIALS AND METHODS

4.1. Predicted changes in frequency distribution curves

Frequency distribution curves provide valuable information on changes in temperatures profiles as measured against a standard period. Fig. 3 shows the types of changes expected to occur with increased global warming and variability projected by climate change models. Fig. 3 shows that only a small change in the curves can result in an increased frequency in hot extremes, and greater intensity of those extremes, plus a reduced frequency in cold extremes.

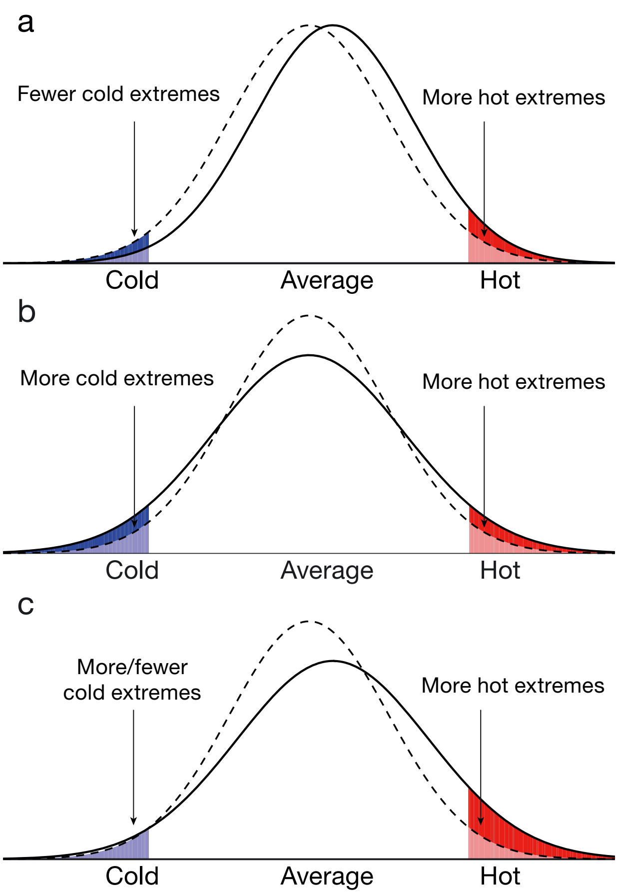

Fig. 3. Schematic indications of changes in temperature distribution on extremes. Increase in (a) mean, (b) variance, (c) mean and variance. Dashed line: normal distribution; solid line: future changes; darker colour hues: changes in temperature intensities. Fig. 3 is adapted from IPCC WGI AR5 Report, Fig. 1.8, p. 134 (Cubasch et al. 2013). Published with permission granted from the IPCC

The probability of occurrence, or frequency, of extremes is denoted by the shaded areas. Changes in the frequencies of extremes are affected by changes (1) in the mean, (2) in the variance or shape, and (3) in both the mean and the variance.

The standard deviation (SD) is a statistical measure associated with the frequency of occurrence curves, and measures the variation from the mean. For this analysis we investigate the changes in the SD ranges of the daily temperatures between two 30 yr periods as measured against the 1961–1990 means. The use of SD ranges rather than locally recorded temperatures also allows for better visualization and relative comparisons in temperature shifts as the temperature range for each geographic location differs.

4.2. Site selection and data source

The 7 sites used in this analysis consisted of 4 coastal towns (Broome, Darwin, Cairns and Normanton) and 3 inland towns (Halls Creek, Tennant Creek and Georgetown) (see Fig. 1). These sites provide a coast-to-coast geographical coverage over northern Australia, given the constraints of the sparsity of long-term observational sites across the region. All are a part of the BOM ACORN-SAT data sets, which provide homogenized temperature records dating back to 1910. (These data sets, along with the methodology used to develop them are freely available at www.bom.gov.au/climate/change/acorn-sat/). Note that although Townsville is the largest city in northern Australia, and lies within our study region, its meteorological records do not cover the full time period of this study, and so had to be excluded.

Unlike temperature, continuous rainfall records were not available for the majority of selected weather stations over the whole period 1911–2014. To rectify this shortfall, rainfall data from the closest available weather stations to these sites were utilized alongside the selected study sites to cover this period. Where the data sets overlap, the data from the most recent open site has taken precedence. Validity of this approach was tested by analysing the monthly data sets over the overlapping periods. Given the strong correlation values in the October–March monthly rainfall totals across all sites, values from the corresponding site have been directly substituted where there is missing data. The rainfall data are summarized in Supplement 2 at www.int-res.com/articles/suppl/c071p001_supp.pdf.

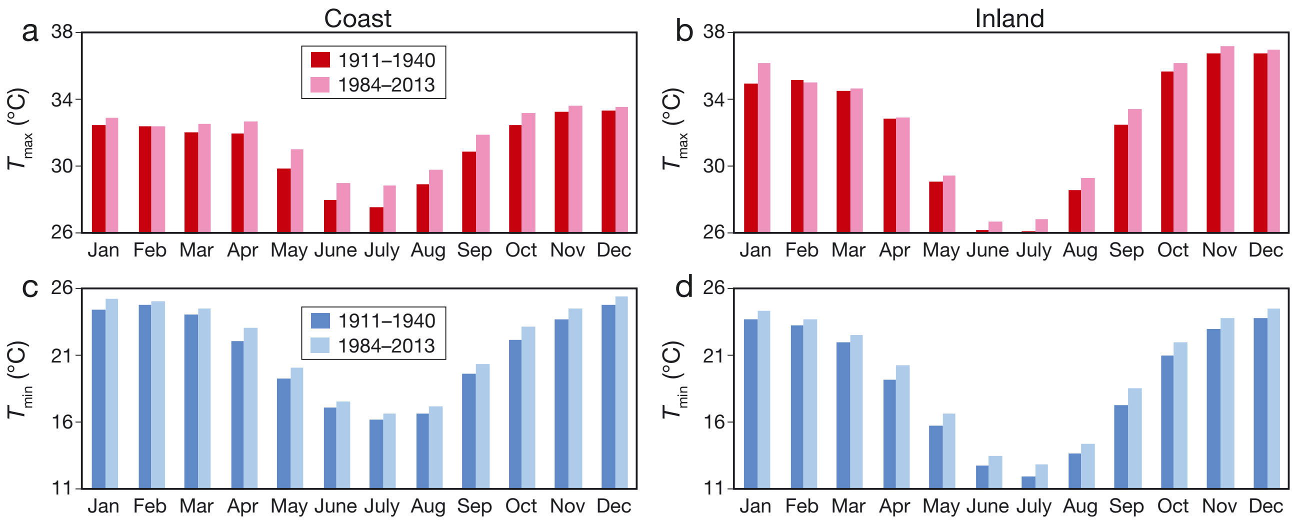

Fig. 4. Comparison of trends in mean daily temperatures by month (a,b) maximum (T_{max}) and (c,d) minimum (T_{min}) across northern Australia between 1911–1940 and 1984–2013. (a,c) Coast, (b,d) inland

4.3. Data analysis

The BOM daily temperature and monthly rainfall data for these sites for the period April 1911 to March 2014 were accessed for this analysis. The monthly and seasonal temperatures were then calculated from the daily data. The T_{max} threshold was selected to reflect Australian evidence of heat response relationships (30°C). In the absence of a validated T_{min} threshold, we selected the T_{min} threshold for the region under study as the average monthly T_{min} exceeded by 6 mo or more (21°C). This is very warm in comparison to the rest of Australia. The highest average monthly T_{min} in Brisbane exceeds 21°C in only 2 mo, while the more southerly capital cities T_{min} varied between 12.1°C in Hobart and 18.8°C in Sydney.

In this analysis we examine the following temperature and rainfall trends.

(1) Identification of the changes in temperature (T_{max} and T_{min}), and in days where T_{max} >30°C and T_{min} >21°C between the two 30 yr periods 1911–1940 and 1984–2013.

(2) Examination of differences in frequency of occurrence of SD values for T_{max} and T_{min} between these 30 yr periods, as measured against the 1961–1990 values. The daily T_{max} and T_{min} for each season within each time period was compared to the 1961–1990 SD values and a curve of best fit applied to each distribution.

(3) Examination of differences in the decadal average temperatures, as measured against the 1961–1990 mean.

(4) Examination of the percentage of years the October–March rainfall within these 2 periods fell outside 1 SD from the mean 1961–1990 rainfall for each location selected.

(5) Comparisons of the average daily maximum and minimum temperatures across all coastal and the inland sites were presented.

Data for all individual sites are provided in the Supplement files.

5. RESULTS: OBSERVED CHANGES IN THE CLIMATE OF NORTHERN AUSTRALIA

5.1. Trends in overall temperatures between 1911–1940 and 1984–2013

Fig. 4 provides an analysis of the changes in the mean daily temperatures by month across the region while Table 1 provides a summary of the differences in the annual mean T_{max} and T_{min} between the 2 periods.

Table 1. Differences in the annual daily maximum (T_{max}) and minimum (T_{min}) temperature for coastal and inland locations between 1984–2013 and 1911–1940

	Mean T_{max} (°C)	Mean T_{min} (°C)
Coast		
1911–1940	31.1	21.2
1984–2013	31.8	21.9
Difference	0.7	0.7
Inland		
1911–1940	32.4	18.9
1984–2013	32.9	19.7
Difference	0.5	0.8

Table 2. Observed daily minimum (T_{min}) and maximum (T_{max}) temperature distribution trends by season (1984–2013 compared to 1911–1940). Percentage changes in frequency of occurrence of standard deviations from the reference period 1961–1990. (Negative values indicate a decrease for the 1984–2013 period compared to the 1911–1940 period and positive values an increase)

Season	SD range ≤−2 C	≤−2 I	>−2 to −1 C	>−2 to −1 I	>−1 to <1 C	>−1 to <1 I	1 to <2 C	1 to <2 I	≥2 C	≥2 I
T_{min}										
Apr–May	−3	−2	−7	−8	−1	3	11	7	0	1
Dry	−2	−3	−3	−3	−1	−2	6	6	0	1
Sep–Oct	−4	−5	−11	−6	5	−2	8	11	2	2
Nov–Dec	−4	−3	−9	−8	2	2	11	24	1	2
Wet	−5	−4	−3	−8	3	6	5	6	1	1
T_{max}										
Apr–May	−2	−3	−3	−5	2	10	2	−2	0	−1
Dry	−7	−4	−12	−2	2	2	13	3	3	2
Sep–Oct	−6	−1	−12	−5	4	−4	10	8	4	2
Nov–Dec	−1	−3	−3	−5	2	10	2	−2	0	−1
Wet	−4	−5	−1	0	2	8	2	−2	−1	−1

tion, as it may just be a result of the homogenisation adjustments used on the individual sites. The largest T_{max} increases were observed during the Dry season in coastal locations, with July recording a 1.3°C increase. The largest increase in T_{min} was observed inland during September, which also recorded a change of 1.3°C.

The impact of these increases on the more extreme temperature range can be seen in Fig. 5, which shows the changes of the number of days >30°C and nights >21°C between the 2 periods (1911–1940 and 1984–2013) by percentage. To account for differences in the total numbers of days for each location between the 2 periods, the changes as a percentage of the 1911–1940 period have been calculated as follows:

[(Difference in days 1911–1940 from total days 1911–1940) − (difference in days 1984–2013 from total days 1984–2013)]/total days 1911–1940

This analysis shows that T_{max} and T_{min} have increased across all coastal and inland sites and throughout the whole year between the 2 time periods. The smallest increase in T_{max} occurred during the Wet season in inland regions, with February actually showing a slight decrease. However, small changes, such as in February, should be interpreted with cau-

The percent of days >30°C and nights >21°C by season are based on the number of days compared to the total days for each period.

Overall the average percentages of days >30°C across the 12 mo period have increased from 67 to 75% for coastal locations (representing an increase of 12% above the 1911–1940 period), and from 71 to

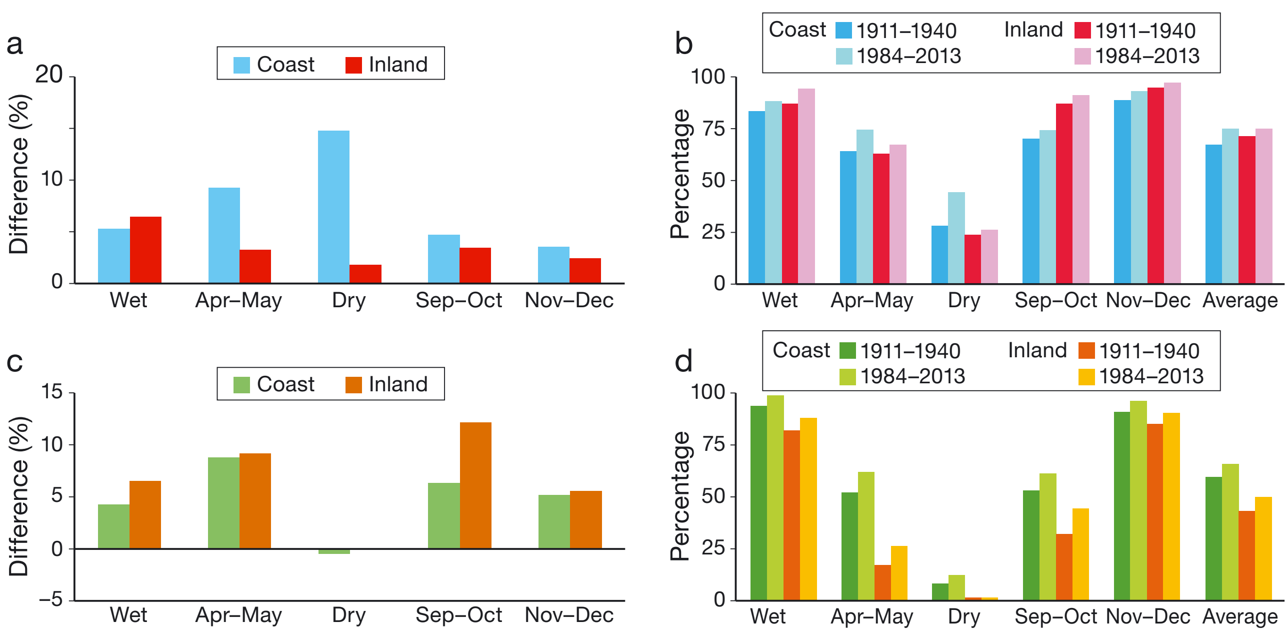

Fig. 5. Percentage change in total days and in overall percent of days (a,b) >30°C and nights (c,d) >21°C for coastal and inland locations between 1984–2013 and 1911–1940

75% for inland locations (increase of 6%) between the 2 periods, with the greatest increase being between April and August. Average percentages of nights >21°C across the 12 mo period between coastal and inland locations have been more consistent, increasing from 60 to 66% (increase of 10%) in coastal locations, and from 43 to 50% (increase of 16%) in inland locations with the greatest increase being during the periods April–May and September–October across the whole region. The increase in minimum temperatures has been the least during the Dry season.

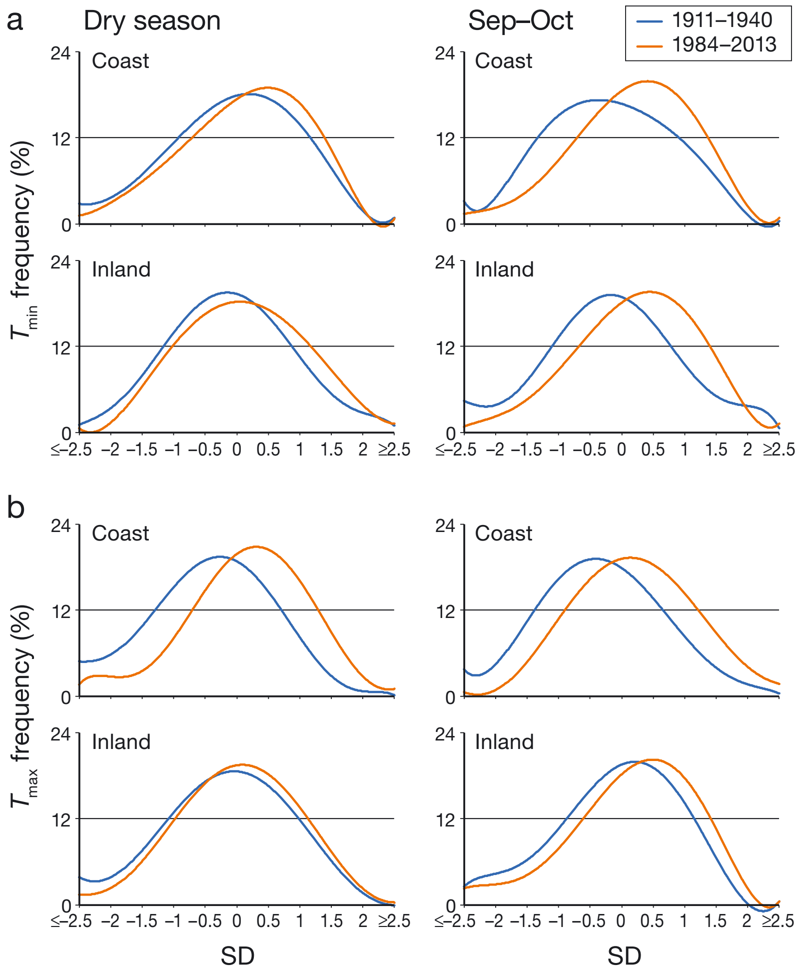

Fig. 6. Curves of best fit for changes in frequency of daily (a) minimum temperature (T_{min}) and (b) maximum temperature (T_{max}) over northern Australia between the coastal and inland stations for the Dry season (left) and the early Build-up (Sep–Oct) (right), between 1911–1940 and 1984–2013, as measured against the 1961–1990 SD values

5.2. Change in frequency of occurrence of T_{min} and T_{max} as measured against the 1961–1990 mean

This analysis compares the frequency of occurrence of the daily T_{min} and T_{max} between the periods 1911–1940 and 1984–2013 against the 1961–1990 SD values. Small shifts in these distribution curves can be associated with large changes in the extent and severity of extreme events, represented by the tails of the curve. The impact of such warming over Australia can be easily demonstrated where a 0.9°C average warming over Australia since 1910 was associated with a 5-fold increase in extreme heat events (Lewis & Karoly 2013).

The seasonal analyses across inland and coastal locations, including the full table of the differences for both T_{min} and T_{max}, are provided in Supplement 3 at www.int-res.com/articles/suppl/c071p001_supp.pdf, while Supplement 4 provides the analysis for each individual location on a month by month basis. Fig. 6 shows the analysis of the changes in these temperature distributions, averaged by location over the Dry season and the early Build-up season (September–October) — the seasons showing the largest overall changes — as measured against the 1961–1990 SD values.

These observed shifts in the distribution curves are consistent with the schematic representation of the impact of warming trends by the IPCC (Fig. 3). The warming signal is most pronounced in the loss of cool nights and cool days. The largest warming trend in T_{max} is observed across coastal locations compared to inland locations, particularly during the Dry season and September–October. The strongest T_{max} warming trends were observed in the inland areas during the September–October period, a period when humidity also starts to rise.

Supplement 5 provides an overview of how the distribution curves have changed. These changes are summarized to highlight where the shifts within the distribution curves have occurred. For both T_{min} and T_{max}, the main changes in the distribution curves between the 2 periods are occurring within the +2 and –2 SD ranges, with a significant shift towards warmer temperatures in the later period. A significant drop can be seen in the extreme low temperature ranges in the later period for both daily T_{min} and T_{max}, across all seasons and locations. In contrast, increases above the +2 SD range (i.e. in extremely hot days) are observed in the Dry season and the September–October season along the coast. Changes in the extreme ranges can have significant impacts and will be analysed in a subsequent study.

Since the annual T_{max} range in this region is relatively small, the actual differences in the +1 and −1 SD values are also correspondingly small. However, as hot climates already stress human thermoregulatory capacity, even small temperature increases can exert large impacts on human health (Glass et al. 2015, Hanna & Tait 2015). A table of the seasonal temperatures and the standard deviations for each location is listed in Supplement 6.

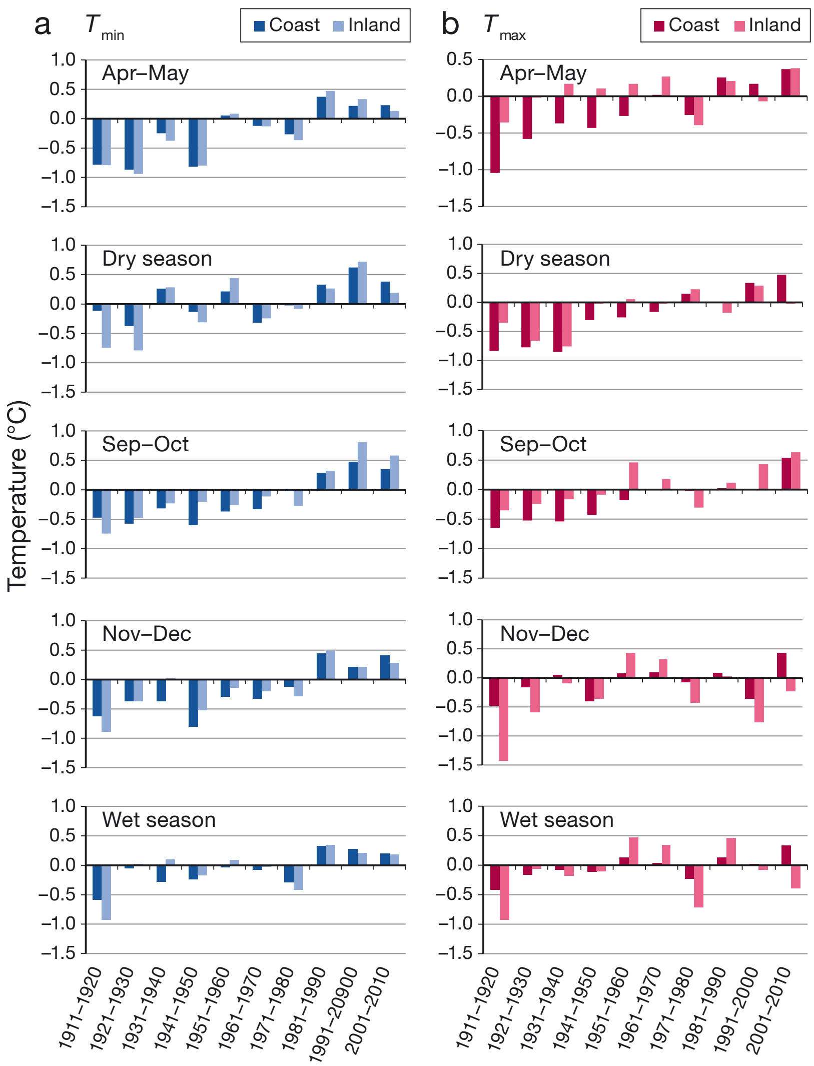

Fig. 7. Observed changes in the seasonal decadal average (a) minimum (T_{min}) and (b) maximum (T_{max}) temperatures from the 1961–1990 averages for both the coastal and inland locations for the period April–October

5.3. Observed changes in temperatures by decade as compared to the 1961–1990 mean

This analysis provides an historical perspective on how climate change has occurred over the period of record by showing the trends and extent of these changes by decade.

Fig. 7 provides a seasonal breakdown of the observed difference in decadal averages from 1961–1990 for T_{min} and T_{max} for the coastal and inland locations.

While there has been a clear regional increase in T_{min} across the decades in all seasons, increases in T_{max} are less pronounced. The trend in increasing T_{max} is evident between April and October, with little warming trend observed between November and March. This is particularly the case during the Wet season, which shows the lowest and more variable trends across the whole period of record. T_{max} at coastal locations is increasing at a greater rate than inland locations. However over the last 2 decades, the situation was reversed during the early Build-up season (September–October) when T_{max} at inland locations has been increasing at a greater rate.

5.4. Observed changes in the October–March rainfall between the 1911–1940 and 1984–2013 periods

Identifying changes in rainfall across a region presents challenges as it is affected by space and time and is often localized in intensity. Australia's large natural rainfall variability dampens the signal in long-term trends, which necessitates a very long dataset to detect trends against this variability. As discussed above, our rainfall analysis was carried out over the individual locations and restricted to the full 6 mo wet period (October–March).

The data clearly reveal the dominant influence of this 6 mo period on the annual rainfall across the region. Cairns is the only location to receive <80% of its annual rainfall during the Wet season. Being located on the east coast, Cairns experiences onshore winds during the Dry season that can bring rainfall during this time of year, whereby its Wet season can extend into April and beyond.

Fig. 8 provides an indication of percentage change observed over these periods in occurrences where the Wet season rainfall was ±1 SD outside the 1961–1990 period. This figure indicates that while there is generally a small decrease in the frequency of drier years, notably in the early Wet season, there were distinctly more wet years in the period 1984–2013 compared to the period 1911–1940. The observed trends indicate that the Wet seasons are now, on average, wetter, with Wet seasons with very high rainfall occurring more often. This accords with global warming projections that a warmer world is also likely to be a wetter world (IPCC 2013) especially in low latitude regions. This figure also indicates that the western and central parts of northern Australia are getting wetter, with an increase in the events >1 SD and a reduction in the events <–1 SD, while there is a slight drying trend in eastern parts. (Note: this data set does not include the current drought in northern Queensland)

While nearly all sites indicate an increase in the percentage of high rainfall years (>1 SD) throughout the Wet season as a whole, for the period 1984–2013 compared to the 1911–1940 period, there is a tendency towards a lower percentage of low rainfall years (<–1 SD), particularly across the whole Wet season.

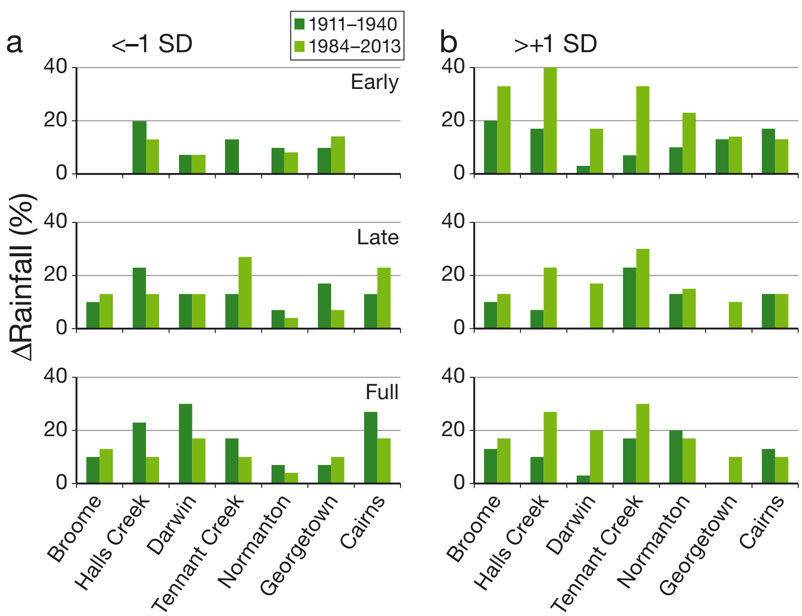

Fig. 8. Percent change between the 1911–1940 and 1984–2013 periods in the Oct–Mar rainfall in the number of occasions (a) below the –1 SD and (b) above the 1 SD levels for the 1961–1990 period for the full Wet season (Oct–Mar), the early Wet season (Oct–Dec) and the late Wet season (Jan–Mar). (Absence of a bar indicates there was no year within that time period where rainfall anomaly fell outside the reference time period SD value)

This indicates that, overall, the Wet seasons have become wetter in the west and central areas for the latter 30 yr period and that this increase is occurring during both the early and late parts of the season.

The Australian Bureau of Meteorology interactive maps of rainfall and temperature trends (available at: www.bom.gov.au/climate/change/index.shtml#tabs=Tracker&tracker=trend-maps) indicate that the sites selected for this study are truly reflective of the broad-scale changes across the region, with rainfall increasing in the west and decreasing in the east.

6. DISCUSSION

6.1. Implications to human health and regional development of observed climate trends

Physiological thermal tolerance is dependent upon a range of determinants, which include personal physical characteristics, behaviours, as well as meteorological parameters such as temperature, wind speed, solar radiation and relative humidity (Tait & Hanna 2015). Whereas this study focussed primarily on 30 yr trends in temperature and rainfall across northern Australia since 1911, subsequent analyses will examine trends in extreme events, and incorporate humidity and WBGT in order to examine human heat tolerance in this tropical region.

This study identified a warming trend in both T_{min} and T_{max} across northern Australia. Differences recorded between the early and later 30 yr periods ranged between increases of 6 and 16%, whereby loss in cool days and nights (<–1 SD) were consistently a few percentage points more than gains in hot days and nights (>1 SD). This T_{max} warming trend is more evident during the Dry and transition periods April–May and September–October in coastal locations. As these locations have higher population densities, any warming trend could therefore amplify the potential for deleterious human impacts. It is possible that the enhanced coastal warming could be explained by warming trends in sea surface temperatures (SST) (maps available from the BOM website www.bom.gov.au/climate/change/index.shtml#tabs=Tracker&tracker=trend-maps).

Despite the overall annual warming trend across northern Australia, a slight cooling was observed over the western regions for the period 1970–2014. However, this western cooling trend is limited to summer (Wet) and winter (Dry), whereas spring (Build-up) continues to show a warming trend. While the cooling during the wet season could be related to an increase in precipitation, the cooling in the mean temperature during the Dry season is thought to be linked to changes in the broad-scale synoptic patterns during winter over southern Australia (Trewin et al. 2015).

The analysis of the wet season rainfall (October–March) indicates a tendency for 1984–2013 to be wetter, with a higher frequency of rainfall events occurring above the 1 SD value based on the 1961–1990 period. The increase in rainfall may be indicating a change in the intensity and number of thunderstorms during the build-up period and in monsoonal low pressure systems or tropical cyclones during the latter part of the wet season, when the monsoon trough is the dominant feature. The change in rainfall patterns, while not indicating a lengthening of the actual wet season, would be expected to lead to an increase in humidity, and thus increase in human thermal discomfort especially during the early build-up season. It can extend the proportion of the year when discomfort and risk of heat stress are very high.

As indicated above, daily maximum temperatures across northern Australia exceed 30°C for up to 9 mo of the year and exceed 33°C for up to 6 mo, with night-time minima exceeding 21°C for over half the year. Also, the warming trend in the early build-up months September–October coincides with the seasonal increase in relative humidity as the dry season comes to an end. The build-up is the most problematic season for mental health problems, alcohol abuse and violence due the heat and high humidity (Purtill 2014). Further exacerbations of these conditions are likely to amplify social disruptions and diminish the liveability and productivity of the region.

Exposure to extreme heat and humidity has a considerable impact on people's lives through associated sleep deprivation (Tsuzuki et al. 2004), and it negatively affects human relationships and mental health (Tawatsupa et al. 2010). Without technology to maintain thermal comfort in such extreme climatic zones, physiological thermoregulatory limits constrain healthy human functioning and survival in hot and humid climates (Hanna & Tait 2015). Those unable to access air-conditioning, such as lower socio-economic groups, commuters and outdoor workers, will be most disadvantaged as heat and humidity continue to escalate.

A combination of heat, humidity and high rainfall also results in conditions suitable for mosquito activity and the spread of disease (Geoghegan et al. 2014, WHO 2015). Negative reactions created by the routine discomfort of itchiness from mosquito bites and fears of disease they carry combine to create a powerful aversion for people to relocate to environments where mosquitoes abound.

Such conditions across northern Australia provide a significant disincentive for many to settle permanently (Bauer 1977), and lead to a highly transient population and a low permanent population base. This high population turnover brings additional difficulties for industry, such as problems related to the retention of experienced staff (Hall et al. 2007, Garnett ST et al. 2008).

Low population density also exacerbates the sense of isolation from family and friends (Carson D 2008) and lack of access to amenities available to larger population centres. For example, isolation has been found to contribute to increased levels of problem gambling amongst mobile construction workers in northern Australia (Doran & Young 2010).

Our findings demonstrate rising temperatures across the whole region, and increases in rainfall in the western parts. Climate model projections indicate further temperature and rainfall changes can be expected in tropical regions which are likely to exacerbate the already difficult living conditions. Thus, the projected increases in population discussed in the 2015 White Paper appear highly optimistic once these factors are included. Exclusion of the potential of climate and climate change impacts from the Federal Government's 2015 White Paper planning documents places the success of development projects based on these documents at significant risk.

6.2. Future climate of northern Australia

Future substantial warming for the northern Australian region for mean, maximum and minimum temperature is projected with very high confidence (Moise et al. 2015). For the near future (2030), the mean projection is for a further 0.5 to 1.3°C warming above the recent climate of 1986–2005, with only minor differences between the IPCC Representative Concentration Pathways (RCPs). However later this century (2090), projections suggest 1.3 to 2.7°C for RCP4.5 and 2.8 to 5.1°C for RCP8.5. This translates to a substantial increase in the temperature reached on the hottest days, the frequency of hot days and the duration of warm spells across the region. For example, CSIRO projections suggest that Broome could experience a doubling of days >35°C, and tripling of days >40°C (Moise et al. 2015).

Given the already difficult climate of northern Australia, the additional heat stress from these projected changes will further exacerbate human health and productivity challenges, while restricting the exposure time for outdoor activity to be safely undertaken during the build-up seasons. Unless significant measures are introduced to ensure cooling is available for outdoor workers, their health and productivity will decline.

Although there is considerable uncertainty in projected changes in monsoonal activity on regional scales, on the global scale the geographical region affected by monsoons is projected to increase over the 21st Century, together with the amount of monsoon rainfall (IPCC 2013). Monsoon onset dates are projected to become earlier or not to change much, and monsoon retreat dates are projected to occur later (Dowdy et al. 2015). This will extend the proportion of the year with high, problematic levels of humidity.

Projected higher rainfall for tropical regions under global warming (CSIRO and BOM 2015) could lead to more extreme rainfall events and the spread of vector-borne disease (Geoghegan et al. 2014), which are recognized globally as 'climate sensitive diseases' (McIver et al. 2015). While there are diverse future rainfall projections from the climate models for Australia, our analysis has demonstrated observed trends towards greater rainfall variability across Australia's north. It is also likely (medium confidence) that while there may be fewer tropical cyclones, an increasing proportion of those are projected to be more intense (Moise et al. 2015). An increase in heavy rainfall events and severe tropical cyclones could lead to an increase in the impacts from flooding or severe wind damage (Ranson et al. 2014). The influences of rainfall patterns on human activity and regional development are many and varied, and the influence of extremes is likely to be dramatic. Their significance makes it imperative for planning to incorporate all available intelligence on rainfall as a key risk mitigation strategy.

7. CONCLUSION

Australian human thermal tolerance has been shown to decrease rapidly once the temperature rises above 30°C. In northern Australia the mean monthly T_{max} is >30°C for ~9 mo of the year, while the mean monthly T_{min} is >21°C for ~7 mo of the year. These conditions indicate that the climate of northern Australia is already at the upper limit of human thermal tolerance, which has adverse impacts on human activity and health. We have identified a trend towards warmer and wetter conditions over the last 30 yr of record compared to the first 30 yr. This trend has resulted in a significant increase in the numbers of days >30°C.

While there has been a general increase in T_{min} across the region throughout the year, increases in T_{max} are influenced by season and location. The more populous coastal locations are warming to a greater degree than inland locations, and mainly during the period April–October, with the largest increases occurring during the dry season. The warming is therefore most pronounced in the critical regions for human exposure and infrastructure projects. While rainfall trends are more difficult to identify, this analysis does show greater variability, with rainfall increasing in the western and inland parts of northern Australia, and an indication of drying in the east.

These observed changes in climate conditions are not only increasing the risks to human health and the long-term viability of development projects, but are currently acting as a deterrent for people to settle permanently in the region. Further warming, as projected by the IPCC climate change scenarios, will amplify these difficulties.

These climatic challenges however are not insurmountable, provided sufficient resources and effort are put towards addressing them from the initial concept phase of all projects. Such efforts are likely to deliver significant health protection and project risk management capacity by safeguarding against ill-informed decisions which could have considerable economic and social ramifications. Without such risk management, the likelihood of a failure of existing and future development projects increases considerably, and may yield unwanted outcomes, such as ultimately hampering capacity of future projects to attract capital; in addition, the potential for deaths is real. Climate change and its threats to human activity should therefore be seen as integral to the planning of development projects, particularly in challenging climatic regions such as northern Australia.

Techniques used in this case study can be readily applied to other climatic regions to investigate other relationships between climate and climate change, human health and other societal and environmental impacts.

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