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CLIMATE CHANGE IN QUEENSLAND'S GRAZING LANDS. I. APPROACHES AND CLIMATIC TRENDS

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Abstract

Climate change is an important global issue but is yet to be recognised as such by many rangelands users. This paper reviews some of the uncertainties relating to pre-instrumental and future climate change and documents current trends and fluctuations in climate of Queensland's grazing lands. Analysis of daily climate surfaces for Queensland's pastoral/cropping zone shows high variability in annual rainfall which is influenced by the El Niño-Southern Oscillation (ENSO) phenomenon. This relationship, when examined using moving windows, has changed during this century with the 1930-40s being a period of low correlation. Minimum temperatures taken from the climate surfaces also changed, showing a significant ($P<0.01$) increase over time especially in May. Over the 40 years since 1957, annual minimum temperatures have increased by 1.0°C for the pastoral/cropping zone and coastal sub-zone, winter minimum temperatures by 1.2°C for the pastoral/cropping zone (1.3°C for the coastal sub-zone), summer minimum temperatures by 0.7°C for the pastoral/cropping zone and coastal sub-zone, and May minimum temperatures by 2.8°C for the pastoral/cropping zone (3.0°C for the coastal sub-zone). Consistent significant trends in vapour pressure (increasing, $P<0.001$) and solar radiation (decreasing, $P<0.05$) also occurred in May. The mechanisms for the identified climate trends and unusual behaviour of ENSO are the subject of speculation with attribution of causes to natural variability or the enhanced greenhouse effect being unresolved. Continued monitoring of these trends and fluctuations will be important for the future management of Queensland's grazing lands with this analysis highlighting the need for discrimination of trends from natural variability. In terms of grazing management and degradation processes, this work also highlights that general changes in climate averages may disguise important variation at yearly and decadal time scales.

Keywords: climate change, Queensland, ENSO, SOI, rangelands

Introduction

The importance of identifying and forecasting possible climatic change resulting from anthropogenic greenhouse gas emissions has been recognised under the United Nations Framework Convention on Climate Change (IPCC 1996). The challenge of formulating policy for mitigating climate change impacts on Queensland's primary industries, especially the extensive grazing industries, is large. This includes ensuring that those involved in the extensive grazing lands are informed of the scientific methodology for determining evidence of global warming, the future impact of the enhanced greenhouse effect, and the role of emission reduction strategies. There has been insufficient information available to assess the importance of climate change as an issue relative to the more immediate problems facing Queensland's grazing industries such as economic viability. To address this deficiency, our papers (Parts I and II) describe the uncertainties associated with climate change, document current climatic trends and fluctuations, and methods for evaluating climate change impacts.

Climate change and greenhouse-related issues have not been given a high priority in surveys of rangelands users (ARMCANZ 1996). For example, the top priorities identified by the grazing industries for the Queensland Department of Primary Industries were security of tenure, commodity prices and seasonal rainfall deficits (P.W. Johnston, pers comm.). Similarly workshops conducted across the nation as part of development of the Draft National Strategy for Rangeland Management (ARMCANZ 1996) identified the top three priority issues as pest management, ecological sustainability and land tenure. Whilst climate change may not have not been explicitly perceived as a priority issue, its potential importance can be assessed through its effects on animal production (including property carrying capacity) and hence economic viability and ecological sustainability.

The decision making process at government level is made difficult by the infancy of the scientific methodology of ascertaining and accurately modelling climate change, and determining the impacts of such climate change on the grazing lands. Many atmospheric and oceanic processes are not yet fully understood nor accurately modelled and the chaotic component of the climate system also limits the capability to make predictions with absolute certainty (IPCC 1996). Thus projections of future climate change will involve a range of possible outcomes rather than a singular prediction from climate models and emission scenarios (Jones 1998).

In order to address some of the difficulties in policy formulation, the Queensland Government has contracted CSIRO Atmospheric Research to prepare future climatic scenarios for Queensland (Suppiah *et al.* 1998). Various types of General Circulation Models (GCMs) have been used but results for rainfall have not been consistent. Hence the future climate of Queensland's grazing lands should be regarded as uncertain.

There are several major sources of uncertainty:

1) the uncertain future change in greenhouse gas emissions and atmospheric concentrations of greenhouse gases (dependent on world population growth, use of fossil fuels, development of alternative energy technologies, and emission reduction policies resulting from the perceived impacts of global warming);
2) the uncertain effects of increased greenhouse gas emissions on global and regional climates;
3) the magnitude of natural variability;
4) the uncertain influence of natural and anthropogenic aerosols and possible feedbacks from the biosphere; and
5) the accuracy of GCMs, Regional Climate Models and Ocean Circulation Models in simulating major phenomena such as the El Niño-Southern Oscillation (ENSO).

To evaluate the importance of climate change for Queensland's grazing lands, given the above uncertainties, we (Queensland Centre for Climate Applications and collaborating organisations) are adopting the following strategy:

1) reviewing existing global and regional climate trends in conjunction with climate projections to identify the possible magnitude of the issue;
2) analysing the sensitivity of the extensive grazing industries to climate variation and change;
3) investigating adaptation and mitigation strategies;
4) continuing the monitoring of key climatic elements; and
5) disseminating information on climatic trends to rangeland users.

To this end, we present a brief review of existing global climate and atmospheric trends and a comprehensive analysis of climatic trends for Queensland's grazing lands. In Part II (Hall *et al.* 1998) we review available production models to assess the impact of climatic variation on Queensland's grazing lands. Concurrent research supporting the above strategy includes evaluation of:

1) impacts studies of climate change scenarios and increased carbon dioxide (CO_2) on rangeland production (McKeon *et al.* 1998, Howden *et al.* 1998);

2) possible adaptation strategies using seasonal forecasting (McKeon *et al.* 1993); and
3) formal evaluation of climate change impacts on typical grazing properties (Campbell *et al.* 1997).

The global concern with climate change (IPCC 1996) has already had a major impact on Queensland's grazing lands through the need to correctly account for greenhouse gas emissions and carbon sinks. Grazing lands have been identified as a major national sink through sequestering carbon in vegetation thickening (Burrows 1995). The grazing lands are also an anthropogenic source of emissions through tree clearing, soil carbon change resulting from land management (Ash *et al.* 1996, Carter *et al.* 1998) and methane emissions from domestic livestock (Howden *et al.* 1996). As global concern to reduce emissions increases, the potential for extensive grazing lands to store carbon could well increase their value both in terms of national finances and allowing Australia to meet national greenhouse emission targets (Burrows 1995, Moore *et al.* 1997, ABARE 1998). However, such analyses are yet to include the impact of climate change on management and production of Queensland's grazing lands.

The climate of Queensland's grazing lands and changes in climate forcing

In this section we review the major features of Queensland's climate and the changes in global climate forcings due to anthropogenic and natural causes. Queensland's climate is a result of its location in the tropics and subtropics (11°S to 29°S) on the western side of the Pacific Ocean. The general circulation pattern in the Pacific Ocean results in a dominant summer south-easterly airstream bringing moisture from warm seas on to the land. Low elevation of the land mass and high solar radiation result in typically tropical/subtropical temperatures and a summer dominant growing season. Most of the region north of 20°S has a climate with distinct wet and dry seasons as a result of seasonal variation in the position of the inter-tropical convergence zone.

Plant and animal growth patterns are dominated by the within-year distribution of moisture with winter temperatures limiting tropical grass growth (Mott *et al.* 1985). However, for some species in the southern tropics, winter temperatures are sufficiently high for growth if moisture and nitrogen are available. Summer isohyets are generally parallel with the coast whilst winter isohyets tend to be aligned in a north-south direction. Thus, each location is a unique combination of summer and winter rainfall, and hence difficulty exists in generalising the impact of climatic trends or change from particular locations. With this reservation we have adopted the approach of averaging climatic elements across large areas of the state to draw general trends.

El Niño-Southern Oscillation

The single most important source of variation in Queensland's year-to-year rainfall is the ENSO phenomenon, the coupling of atmospheric circulation patterns with quasi-periodic (2-5 years) ocean circulation changes in the Pacific Ocean (Allan 1988). The Southern Oscillation Index (SOI) is a well accepted measure of this coupling of atmosphere and ocean and is calculated as an index of the difference in surface atmospheric pressure between Tahiti and Darwin (Allan *et al.* 1996a).

Under El Niño type conditions (i.e. SOI strongly negative), when eastern Pacific sea temperatures are warmer than average, below average rainfall in Queensland is likely (McBride and Nicholls 1983). In some locations (e.g. north-east Queensland) the chance of severe drought (<60% of average summer rainfall) doubles in El Niño years (McKeon *et al.* 1990). Under La Niña conditions (i.e. SOI strongly positive), when eastern Pacific sea surface temperatures are colder than average, Queensland is likely to experience above average rainfall (Allan 1988) including a greater chance of tropical cyclones crossing the coast (Partridge 1994). Regions in Queensland differ in both the strength of correlation between rainfall and the

SOI, and the time of year when these correlations are strongest (McBride and Nicholls 1983, Nicholls 1984, Clewett *et al.* 1991, Stone *et al.* 1996a).

Changes in radiative forcing

Current scientific understanding predicts that the planet's energy balance and global climate are likely to change due to changes in anthropogenic emissions of greenhouse gases (e.g. CO_2, CH_4, N_2O), sulphate aerosols and natural causes (solar variability, volcanic emissions; IPCC 1996, Santer *et al.* 1996). However, climate variations can also occur without a change in external forcing due to the complex interactions between atmospheric and oceanic environment (IPCC 1996).

As the understanding of climate processes has improved more emphasis is now being placed on GCM scenario development as a means of predicting future consequences of possible trends in anthropogenic and natural climate forcing. The combination of GCM studies and other evidence has led scientific bodies to conclude that 'the balance of evidence suggests a discernible human influence on global climate' even though uncertainties still exist as to the magnitude and nature of this change (IPCC 1996).

Radiative forcing due to changes in greenhouse gas concentrations since pre-industrial times is estimated to be +2.45 W/m^2 representing approximately 1% of the 235 W/m^2 of net energy currently received from the sun and available to warm the Earth's surface and atmosphere (IPCC 1996). When the negative forcings of anthropogenic aerosols, change in cloud properties and volcanic aerosols are included, the net change in radiative forcing is approximately +1.5 W/m^2. The global mean temperature has also increased by 0.3 to 0.6°C since the late 19th Century (IPCC 1996). If annual anthropogenic CO_2 emissions continue to increase linearly to be approximately 280% of current rates in 2100, atmospheric CO_2 concentrations will double resulting in a likely change in radiative forcing of +6 W/m^2 and a 'best estimate' of a 2°C increase in global mean surface air temperature relative to 1900. IPCC (1996) in considering a range of emission scenarios and climate sensitivities suggest a projected global mean surface temperature increase of 0.9 to 3.5°C.

Variation in solar irradiance and volcanic aerosols have been identified as possible causes of global temperature fluctuations during pre-industrial times (Mann *et al.* 1998). For eastern Australia Ward and Russell (1980) and Noble and Vines (1993) have suggested possible links between solar variability and decadal climatic variability over the past 100 years but as yet the mechanisms are just beginning to be investigated with GCMs (Robock 1996).

Changes in sea surface temperatures

Global warming is most apparent in the last 20 years (Mann *et al.* 1998). GCM simulations initialised with observed patterns of global sea surface temperatures (SST) have shown a greater influence of tropical rather than mid-latitude SSTs in simulating global warming. The "unusual warmth of the tropical SST since the mid-1970s, during the warm phase of ENSO, has imprinted an unusual warmth on the entire global circulation" (Dickinson *et al.* 1996). Thus ENSO is a major contributor to natural SST variability in the tropics, as well as globally (Dickinson *et al.* 1996, Graham 1994). Several studies have indicated a marked shift in the ENSO pattern in 1976-77 (e.g. Graham 1994). This pattern shift has been explained by Zhang *et al.* (1998) as the teleconnection of extratropical sub-surface thermal anomalies to the tropics. The identification and inclusion of this particular physical pattern in GCM simulations may improve prediction of decadal-scale climate variability (Zhang *et al.* 1998).

Changes in ENSO variability since the 1970s

The above studies suggest that the possible changes in ENSO behaviour have far-reaching global and regional (Queensland) implications. The consistently negative pattern of SOI from

1989 to 1998 represents anomalous behaviour not evident elsewhere in the 120-year time series (Nicholls *et al.* 1996). However, some of the pre-1935 data for Tahiti are missing making it difficult to compare the length of the post-1989 period of negative SOI with earlier periods (Nicholls *et al.* 1996). Trenberth and Hoar (1996) fitted statistical models to the complete 1882 to 1981 Darwin data and determined that the 1990 to 1995 behaviour had a probability of natural occurrence of about once in 2000 years. Independent data sources such as changes in SSTs, upper ocean heat content, surface winds, and satellite-inferred precipitation are consistent with 1990-1995 being warmer than normal in the tropical Pacific region (Goddard and Graham 1997). However, alternative views have been expressed by other researchers. Examination of pre-instrumental records of El Niño and La Niña events reconstructed from proxy tree-ring data shows that persistent, multi-year El Niño events are not unique to the instrumental record period (Allan and D'Arrigo 1998). Nevertheless Allan and D'Arrigo (1998) noted that the 1990-95 persistent event "is the longest historical occurrence observed in the instrumental record."

A major limitation for the Queensland region is that most GCMs are yet to include an accurate simulation of ENSO (Dickinson *et al.* 1996), and hence climate change scenarios for Queensland in the 21st century have a high degree of uncertainty, especially with regard to future rainfall. The GCM study of Wilson and Hunt (1997) is an exception in that the GCM accurately simulated the characteristics of observed ENSO events. Model simulations under doubled CO_2 ($2xCO_2$) scenarios in this study confirmed "that ENSO is a robust feature of climatic variability and persists under greenhouse conditions" with slightly reduced ENSO amplitude and an increase in ENSO frequency. The model also simulated enhanced mean rainfall over north-eastern Australia. However, Wilson and Hunt (1997) state that these scenario indications must be viewed cautiously given the short duration of the simulation experiment and the uncertainty regarding the equilibrium or transient approaches to simulating the impact of $2xCO_2$.

Temporal rainfall variability in the pre-instrumental period

Temporal variability in rainfall is a major issue in northern Australian grazing lands, affecting pasture and animal production, land and pasture degradation, pasture development and expected carrying capacity (McKeon *et al.* 1990). Reconstruction of paleo-climatological records has highlighted the limited experience that is actually provided by the last 100 years of instrument records. Lough (1991) found that fluorescence of bands in coral sampled at the mouth of the Burdekin River were correlated with stream flow and regional rainfall. The fluorescence records from 1735 to 1980 suggest that drier and wetter decadal and 30-year periods occurred in the previous century (1800s) than have been experienced since 1900. The 10-year periods of maximum and minimum fluorescence were 1890-1899 and 1849-1858 respectively. The 30-year periods of maximum and minimum fluorescence were 1870-1899 and 1839-1868 respectively. However, the severe drought year of 1902 (Daly 1994) had the lowest fluorescence value (i.e. driest) in 245 years of record.

Recent research using additional fluorescence time series (Isdale *et al.* 1998) has extended the period of reconstruction back to AD 1644, thus providing an extended record for the consideration of interannual to decadal climate variability of 337 years. Burdekin River runoff was reconstructed using a non-linear transformation of fluorescence data and showed that the period of instrumental record (1922 to 1980) was characterised by a lower median value (25%) than calculated in the independent period of reconstruction (1644 to 1921). In contrast to the earlier study (Lough 1991), Isdale *et al.* (1998) showed that the driest 10 and 30-year periods were 1961-1970 and 1919-1948 respectively. The wettest 10 and 30-year periods were 1670-1679 and 1656-1685 respectively. These contrasting views have different implications in the way that we evaluate the recent drought periods (e.g. 1930s, 1960s and 1990s) relative to possible climatic variation. Some resolution of this issue is required before this information can be effectively used in landuse policy such as expected carrying capacity. Nevertheless both studies suggest a greater range in rainfall has occurred previously than is recorded in the instrumental record.

Climate and atmospheric trends for grazing lands of Queensland

Plant and animal growth, and survival are determined by climatic and atmospheric variables such as CO_2 concentration, solar radiation, air temperature, humidity, and available soil moisture. In the following analyses, general plant and animal responses to existing trends in climatic and atmospheric variables are considered to provide a guide to likely impacts.

Changes in atmospheric CO_2

Since pre-industrial times CO_2 has increased from 280 ppmv in 1800 to 315 ppmv in 1957, to 358 ppmv in 1994 (IPCC 1996). This overall increase of 28% is mainly as a result of fossil fuel burning and landuse change. Here we address the possible effects of increased CO_2 on reducing plant transpiration, and hence increasing air temperature. The effects on increasing plant growth and changing nutrient cycles and animal nutrition are briefly reviewed in Part II.

Increased CO_2 levels tend to close plant stomata, thus decreasing transpiration per unit leaf area (Gifford 1997). Transpiration removes heat from leaf surfaces as latent heat rather than sensible heat, thus resulting in lower atmospheric temperatures than would otherwise exist. Consequently there have been suggestions that increased CO_2 concentration could increase regional temperatures (Pollard and Thompson 1995, Sellers *et al.* 1996, Gifford 1997).

However, the CO_2 effects on evapo-transpiration could be largely ameliorated by leaf area increases in proportion to the reductions in stomatal conductance (e.g. Gifford 1988) and/or the seasonal distribution of transpiration.

Resolution of the impacts of CO_2 on regional temperatures will require regional climate models to incorporate a dynamic vegetation model. Detection of this effect will be difficult without benchmark measurements of plant function and climatic variables in natural situations (rather than at cleared meteorological sites).

Rainfall amount and variability

From the viewpoint of processes in grazed ecosystems, the important attributes of rainfall include amount, seasonal distribution, variability, correlation with global driving forces such as ENSO and daily intensity. Because of the differing rainfall climatologies across Queensland, we have calculated mean rainfall for the pastoral/cropping zone and the coastal sub-zone of the state using daily climate surfaces generated from Bureau of Meteorology data using interpolation techniques (Tabios and Salas 1985, Hutchinson 1991, Carter *et al.* 1996). Rainfall surfaces were available from 1890 to 1996 and surfaces for other climatic variables from 1957 to 1996. The pastoral/cropping zone (approximately 1,095,000 km^2), delimited as the area east of 19°S 140°E to 29°S 144°E and west of 152°E, contains over 70% of Queensland's sheep and cattle (expressed as beef equivalents). We also analysed the coastal sub-zone (approximately 439,000 km^2), delimited from 19°S 144°E to 29°S 150°E, as a separate area. This coastal sub-zone contains a relatively high proportion of Queensland's animal numbers (40%) and has recently experienced severe rainfall deficits associated with the 1990-95 ENSO events.

The analysis of rainfall for these two defined regions showed that a high year-to-year variability (Fig. 1a,b) exists even when averaged across such large areas. Trends were examined using linear regression and cube root transformation of rainfall. For the pastoral/cropping zone and the coastal sub-zone only the month of June had a statistically significant ($P<0.05$) trend (marginal decline) in rainfall. September rainfall also had a significant negative trend ($P<0.05$) for the coastal sub-zone. The high year-to-year variability across large areas highlights the potential impact of large scale climate forcings (such as ENSO) on Queensland's grazing industries, reducing the options of these industries as a whole to dampen the effect of such variability. The four-year running means also exhibit high variation between longer periods. In particular, the declining periods of rainfall, e.g. 1894 to 1902, 1956 to 1965, 1976 to 1982, represent those times in which inflated expectations of rainfall and stocking rates came into conflict with actual climatic reality (Tothill and Gillies 1992). Similarly there has been a distorted view of the actual frequency of 'drought' resulting in some regions being 'drought declared' over 30% of the time (Daly 1994). Year-to-year variability (measured by a moving standard deviation) does not appear to be constant with the 13-year period 1926 to 1949 having a lower year-to-year variation (McKeon *et al.* 1998). The high annual and decadal variability, and the lack of trends over the last hundred years cautions against linking recent rainfall anomalies to global warming trends unless supported by a more mechanistic understanding.

Four-year mean annual rainfall for the coastal sub-zone for the period April 1992 to March 1995 (451 mm) was not as low as the worst four-year period on record, April 1900 to March 1903 (438 mm). However, extreme rainfall deficits have occurred in eastern Queensland at some locations during this period. Butler (1996) reported that rainfall for 1991-5, for seven example stations in coastal Queensland from Beaudesert (28°S) to Townsville (19°S) were the lowest in the whole record (>100 years in most cases). The greatest number of record low rainfall months took place during the early development of the event, particularly during 1991 (Butler 1996).

Given the extreme rainfall deficits experienced at particular locations during this period, it is not unreasonable to expect major effects on agriculture and natural ecosystems, e.g. substantial death of adult trees (27%) were recorded in the Charters Towers region (Fensham 1998, A. Ash pers. comm.). The drought period had a major impact on agricultural production and human well-being with total Queensland rural debt increasing by $200 million during 1995 (Anon. 1996). In 1996 it was estimated that Queensland rural farm-gate losses since 1991 totalled $3 billion, and the Queensland and Commonwealth Governments had spent more than $307 million on drought assistance in Queensland since July 1991.

From the viewpoint of biodiversity in the grazing lands, it is likely that recent droughts have changed ecosystem functioning. With improved animal husbandry, more pasture and browse is likely to have been consumed by domestic stock resulting in fewer fires and changed flows of carbon and nutrients in grazed ecosystems (Gardener *et al.* 1990, Burrows 1995).

Tropical cyclones

Tropical cyclones can contribute important quantities of rainfall to Queensland's grazing lands especially if they cross the coast and become rain depressions (Partridge 1994). The number of tropical cyclones observed in Australia has declined since the start of reliable satellite observation (1969/70) reflecting the greater incidence of negative SOI phases (Nicholls *et al.* 1998). However the number of intense cyclones has increased slightly (10-20%). This would be expected given that only intense cyclones could overcome the physical blocking mechanisms apparent during El Niño years (K. Walsh, pers. comm.).

Temperature

Analysis of trends in temperature require particular attention as possible changes in the location of stations, methods of measurement, calibration of thermometers and local influences such as urban heating may have influenced the station data. Plummer *et al.* (1995) and Torok and Nicholls (1996) using high quality temperature records found recent warming trends over Australia. Minimum temperatures have risen by 0.85°C per century and maximum temperatures by 0.39°C per century (Wright *et al.* 1996). The greatest increases in night-time temperatures have been over the north-eastern interior during the second half of the century (Nicholls 1997). Wright *et al.* (1996) observed that "more than half of the top twenty warmest years since 1910" have occurred in the 1980s and 1990-95, i.e. in the last 15 years.

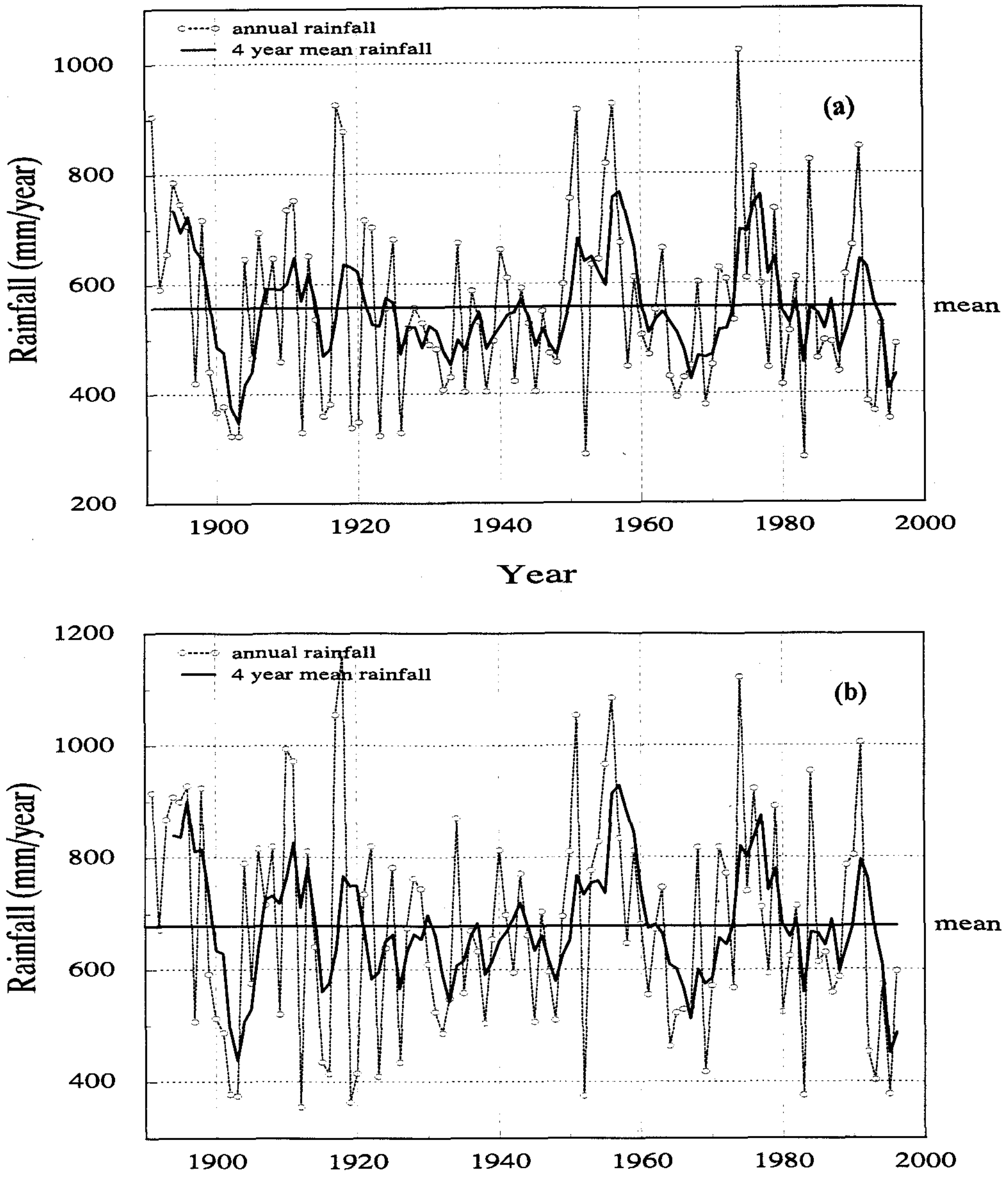


Fig. 1. a) Queensland's pastoral/cropping zone annual (1 April - 31 March) rainfall and four-year running mean of rainfall, and b) Queensland's coastal sub-zone annual (1 April - 31 March) rainfall and four-year running mean of rainfall.

For the stations in Torok and Nicholls' (1996) data that occur in Queensland's pastoral/cropping zone, we found minimum temperature increased since the 1970s (Fig. 2b) whilst there was no trend in maximum temperatures (Fig. 2a). Mean annual maximum and minimum temperatures were also calculated from the daily climate surfaces for the pastoral/cropping zone and coastal sub-zone of Queensland described previously. To check for possible errors in using the daily climate surfaces, the trends in maximum and minimum temperature have been compared with the relevant sub-set of Queensland stations from Torok and Nicholls (1996). The two series of data were highly correlated (r^2=0.964, P<0.001 for maximum temperature; r^2=0.927, P<0.001 for minimum temperature; Fig. 3a,b). The residuals for minimum temperature, i.e. Torok and Nicholls' annual value minus climate surface, increased significantly (r^2=0.35 P<0.001) with time. The differences between these two series were due to different spatial weightings given to stations, i.e. the surface data are appropriately spatially weighted by the process of fitting the daily climate surface whilst we have calculated an unweighted mean of Torok and Nicholls' (1996) stations. The near-coastal stations which dominate the Torok and Nicholls' (1996) sample are also from the regions with greater warming (McKeon *et al.* 1998).

The analyses of temperature trends were conducted for both zones using simple linear regression for: individual months; the seasons of summer (October-March) and winter (April-September); annual periods for calendar year (January to December) and 'ENSO year' (April to March). Significant increasing trends in minimum temperature for the pastoral/cropping zone were found for January (P<0.01), May (P<0.001), December (P<0.05), summer (P<0.01), winter (P<0.01) and annual (P<0.001). Trends were similar for the coastal sub-zone with the addition of a significant increasing trend in February (P<0.05). Significant increasing maximum temperature trends for the coastal sub-zone occurred only in January and March (P<0.05).

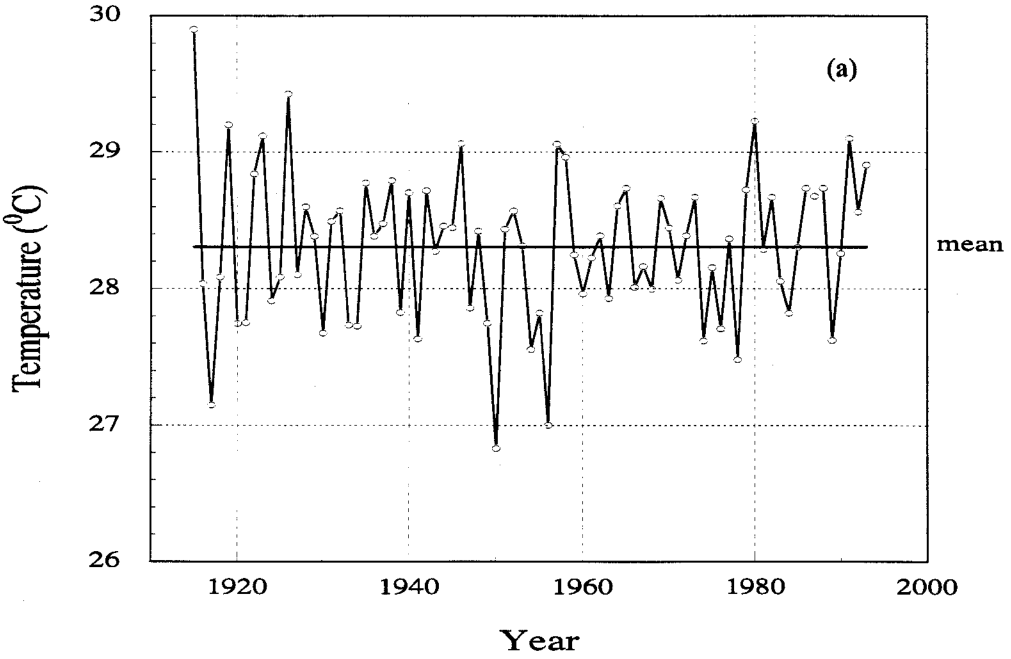
Over the 40 years since 1957, annual minimum temperatures have increased by 1.0°C for the pastoral/cropping zone and coastal sub-zone (P<0.001), winter minimum temperatures by 1.2°C for the pastoral/cropping zone (1.3°C for the coastal sub-zone, P<0.01), summer minimum temperatures by 0.7°C for the pastoral/cropping zone and coastal sub-zone (P<0.01), and May minimum temperatures by 2.8°C for the pastoral/cropping zone (3.0°C for the coastal sub-zone, P<0.001). Rates of change for May, seasonal and annual periods are shown in Table 1.

Vapour pressure, vapour pressure deficit and solar radiation

Vapour pressure, vapour pressure deficit (VPD) and solar radiation from the climate surfaces were analysed as for minimum and maximum temperature. Solar radiation was calculated using the technique of Carter *et al.* (1996), which uses cloud oktas and extra-terrestrial radiation, and accounted for 89% of the variation in measured solar radiation data for all available stations and records. Significant increasing trends in vapour pressure for both zones were found for May only (P<0.001). For solar radiation in the coastal sub-zone there was an increasing trend in March (P<0.05) but decreasing trends in April and May (P<0.05), and an overall decreasing trend in winter (P<0.05). For solar radiation in the pastoral cropping zone only May and the winter season showed significant declining trends (P<0.05). The only significant (P<0.05) trend in VPD was an increase in March for the coastal sub-zone. Rates of change for May, seasonal and annual periods are shown in Table 1.

Trends in May climate variables

The above analyses showed that significant trends were occurring in May climatic variables of minimum temperature, vapour pressure and solar radiation (Fig. 4). The increase in May minimum temperature alone accounts for approximately 25% of the annual increase and 40% of the winter increase (McKeon *et al.* 1998).



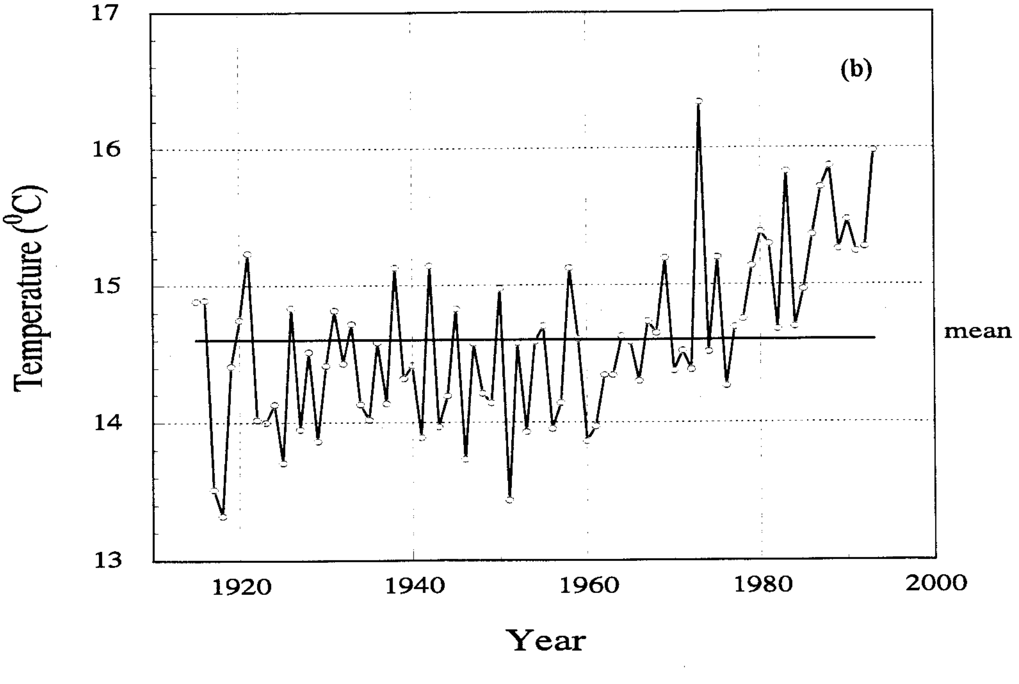


Fig. 2. Annual a) maximum and b) minimum temperatures averaged for stations in Queensland's pastoral/cropping zone from the data set of Torok and Nicholls (1996).

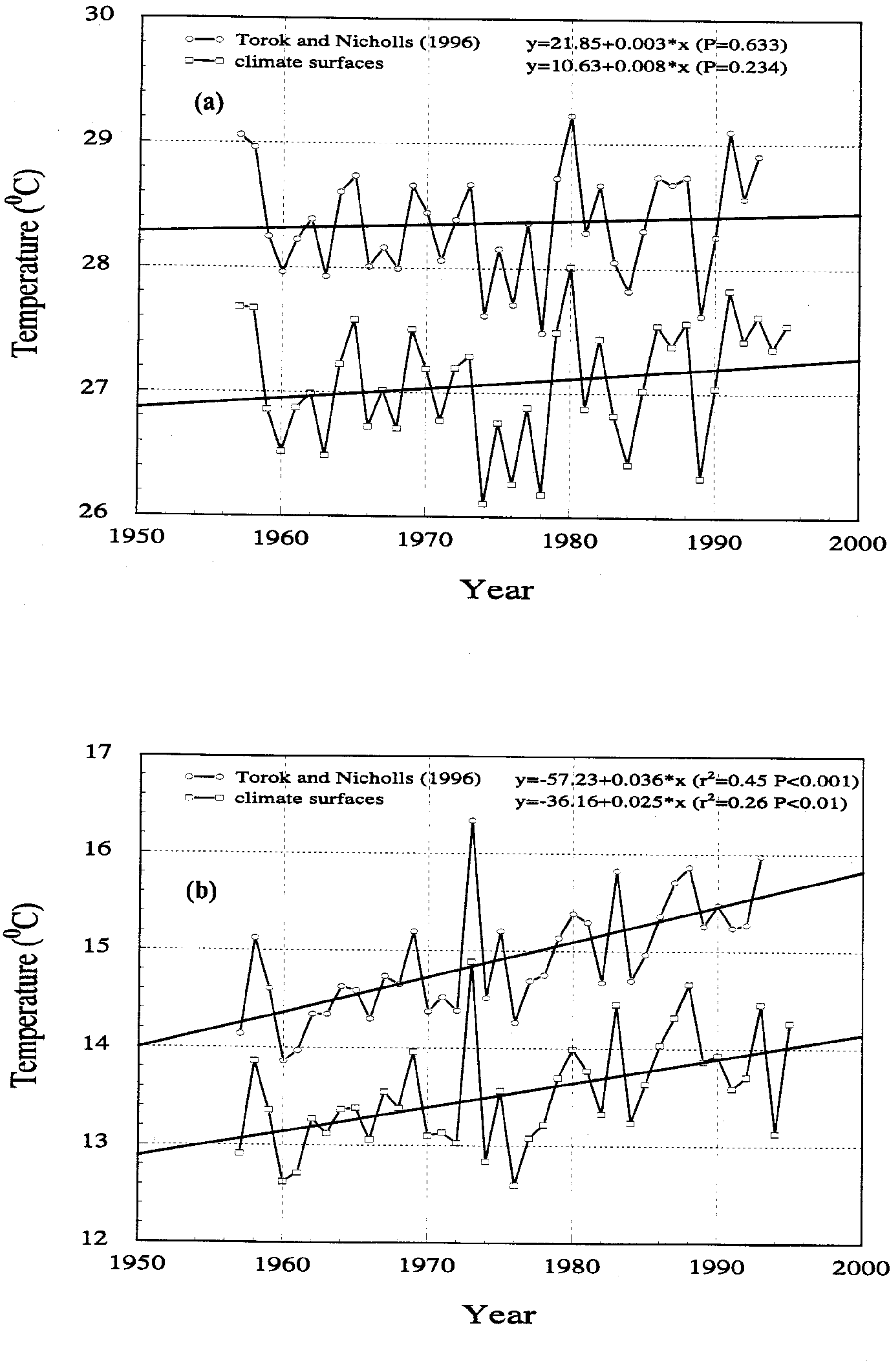


Fig. 3. Comparison of a) Queensland pastoral/cropping zone annual (Jan. - Dec.) maximum temperatures from Torok and Nicholls' data (1996, Fig. 2a) and climate surfaces (r^2=0.964, P<0.001), and b) Queensland pastoral/cropping zone annual (Jan. - Dec.) minimum temperatures from the Torok and Nicholls' data (1996, Fig. 2b) and climate surfaces (r^2=0.927, P<0.001).

Table 1. Rate of change per year of key climate variables averaged across Queensland's grazing lands.

		Climatic variable			
Time period	**Zone**	Minimum temperature (°C/year)	Maximum temperature (°C/year)	Vapour pressure (hPa/year)	Solar radiation (MJ/m^2/year)
May	past./crop.	**0.070*****	0.024^{ns}	**0.066*****	**-0.031***
	coastal	**0.075*****	0.035^{ns}	**0.069*****	**-0.033***
Jan. - Dec.	past./crop.	**0.025*****	0.008^{ns}	0.015^{ns}	-0.004^{ns}
	coastal	**0.026*****	0.010^{ns}	0.014^{ns}	0.001^{ns}
April-	past./crop.	**0.024*****	0.008^{ns}	0.014^{ns}	-0.004^{ns}
March	coastal	**0.025*****	0.010^{ns}	0.013^{ns}	0.001^{ns}
Summer	past./crop.	**0.019****	0.010^{ns}	0.004^{ns}	0.009^{ns}
(Oct.-Mar.)	coastal	**0.018****	0.016^{ns}	0.002^{ns}	0.020^{ns}
Winter	past./crop.	**0.030****	0.009^{ns}	0.018^{ns}	**-0.016***
(Apr.-Sept.)	coastal	**0.032****	0.007^{ns}	0.018^{ns}	**-0.017***

^{ns} not significant (P>0.05)
*P<0.05 ** P<0.01 *** P<0.001

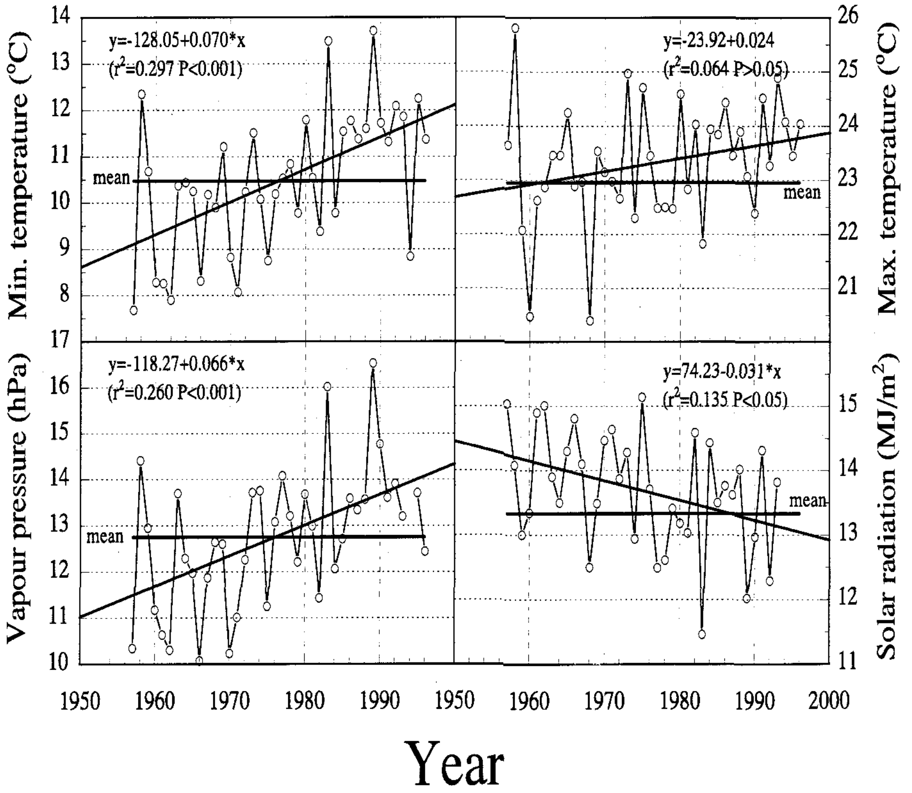


Fig. 4. Climatic variables in May for Queensland's pastoral/cropping zone: minimum temperature; maximum temperature; vapour pressure; and solar radiation.

The large trend observed in May minimum temperatures was not evident in June with similar trends in both the pastoral/cropping zone and coastal sub-zone (not shown). The trends in May for vapour pressure and 'solar radiation' (Fig. 4) are consistent with humidity increases and decreasing solar radiation. There was only a small trend in May maximum temperature which was not statistically significant (P=0.115). The anomalous warm May of 1958 (Fig. 4), especially the high maximum temperature has been confirmed by inspection of individual station data.

The increases in May minimum temperature and vapour pressure follow the expected relationship between saturated vapour pressure and temperature (Fig. 5). These trends indicate that the warm humid season is extending later into autumn but few effects are carried over to June. Although there are no trends in June minimum temperature or vapour pressure, nevertheless, these variables have the same expected relationship between temperature and saturated vapour pressure (Fig. 5).

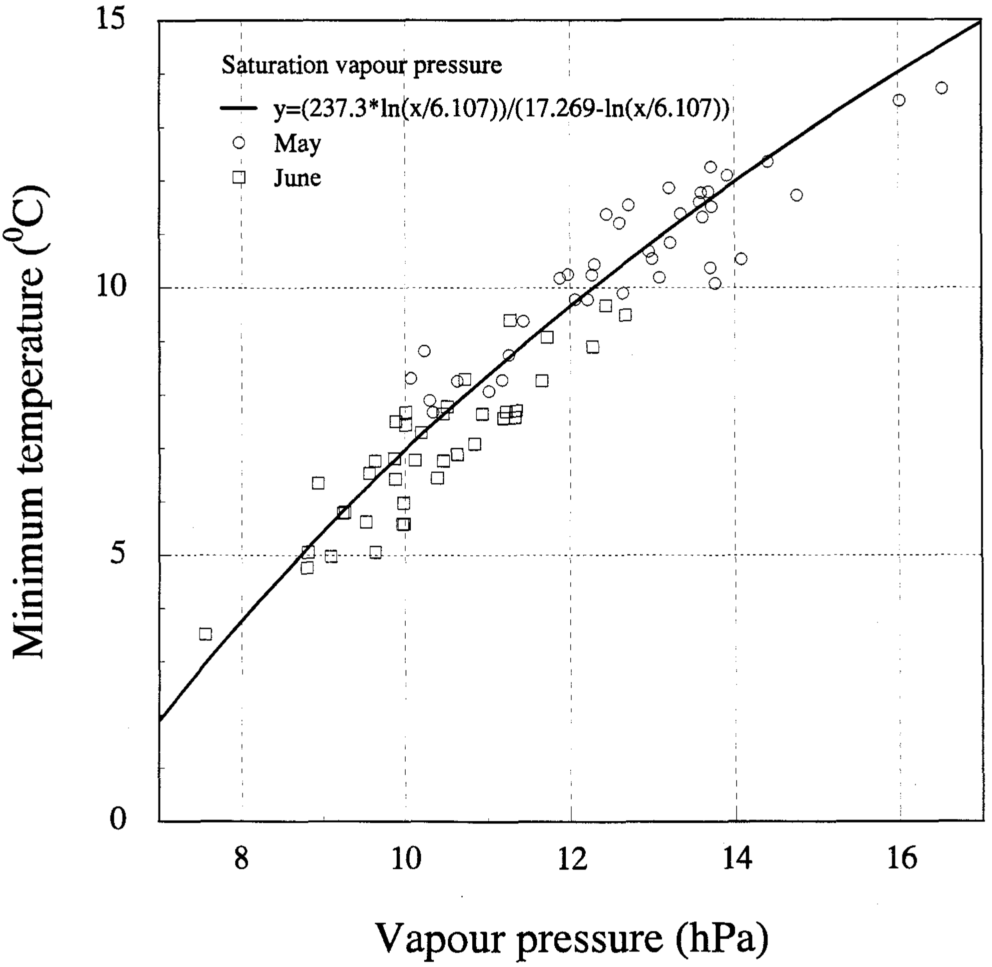


Fig. 5. Relationship between minimum temperature and vapour pressure for May and June in Queensland's pastoral/cropping zone. The plotted line is the relationship between saturated vapour pressure and dew-point temperature.

Although solar radiation in May has been declining, mean May maximum temperature has increased slightly (P = 0.115). The mean diurnal temperature range was highly correlated with solar radiation for both the May and June time series (Fig. 6) suggesting that the slightly increasing May maximum temperatures were due to the fact that the increase in minimum temperature more than compensated for the decline in solar radiation.

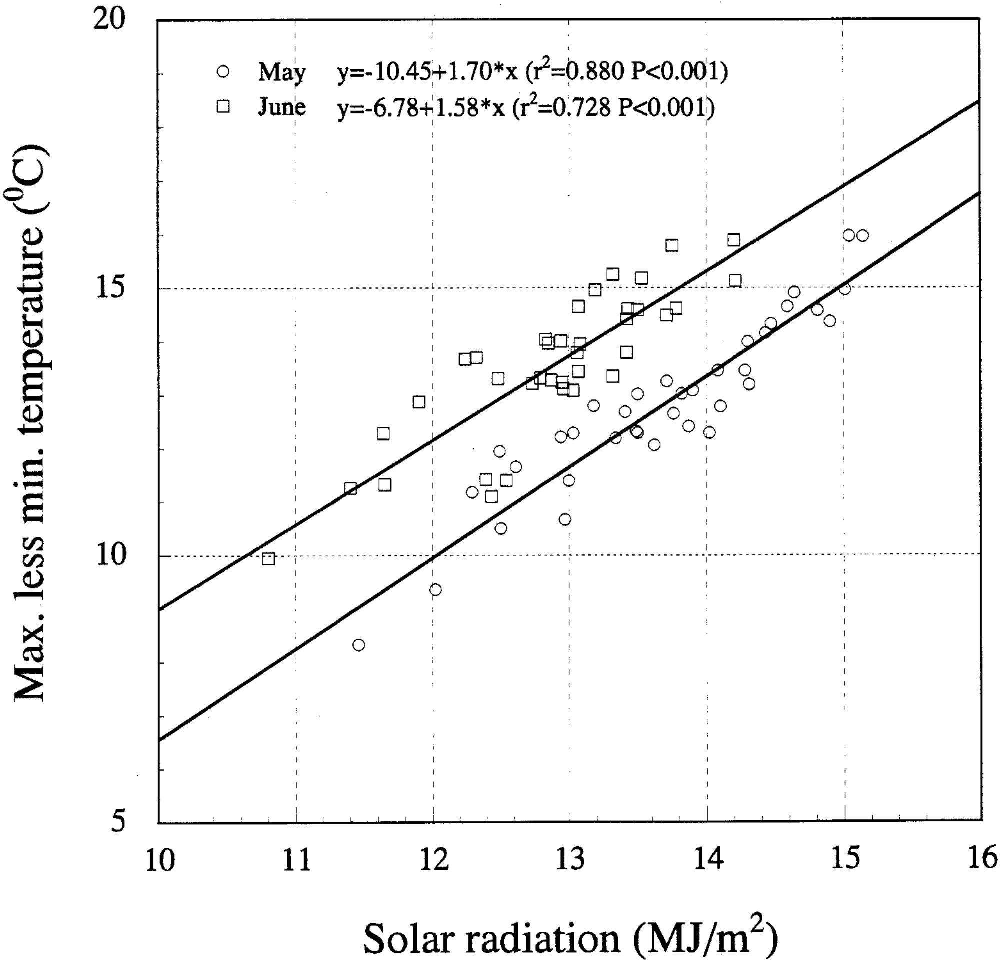


Fig. 6. Relationship between the difference in maximum and minimum temperature and solar radiation for May and June in Queensland's pastoral/cropping zone.

A mechanistic understanding of the larger increases in May temperature and vapour pressure compared to other months is provided by analysis of independent atmospheric and oceanic variables in the Australasian region. From 1950 to 1991, Mean Sea Level Pressure (MSLP) in May has increased in the Tasman Sea (35-40°S) suggesting stronger anticyclonic circulation. This increase in MSLP is associated with increases in north-east low level winds over most of eastern Australia possibly explaining the anomalous source of increased humidity and associated night-time temperatures. April, and particularly June, show weaker trends in MSLP than occurred in May. The April MSLP trend reveals a shift towards more north-easterly flows but not nearly as strongly as occurs in May which may explain why the temperature trend is larger in April than June but less than May. It is possible that the warming in the Indian Ocean SSTs has contributed to the MSLP trends as elevated pressures in the south Tasman Sea can be associated with anomalously warm Indian Ocean SSTs (Simmonds 1990), though the evidence is not conclusive.

Frost and temperature extremes

Frost can cause a rapid decline in forage quality and animal nutrition from tropical pastures (Wilson and Mannetje 1978) and adversely affect winter crop production (Stone *et al.* 1996b, Nicholls 1997). Stone *et al.* (1996b) examined the frequency of frosts at several locations in Queensland and NSW (Emerald, Biloela, Roma, Dalby, Goondiwindi, Charleville, Tamworth, Dubbo, Moree) where long-term daily data were available. Regression analysis suggested a downward trend in numbers of frosts over the period of record (at the 95% confidence level) at six of the nine stations: Emerald, Biloela, Roma, Dalby, Goondiwindi and Tamworth. Regression lines calculated for dates of last frost over the period of record suggest a trend towards earlier date of last frost at five of the stations: Emerald, Biloela, Roma, Goondiwindi and Tamworth. Trends at the locations analysed may reflect the influence of their proximity to a warming Coral Sea (Stone *et al.* 1996b). The warming in May and earlier date of the last frost suggest a contraction in the frost period.

Daily climate extremes are important for biological processes especially those associated with reproduction and mortality of organs and organisms (seed production, bud survival, sperm production, embryo development, animal and plant death). With the exception of rainfall, daily climate records are not readily available before 1957. For Queensland there are only five stations where computerised daily temperature records are available for the period 1894 to 1957 (Stone *et al.* 1996b) and hence the electronic data entry of archived data is a high priority if changes in extremes (e.g. Stone *et al.* 1996b) are to be detected.

Plant growth indices

Increasing May temperatures, shorter frost periods and increased winter temperatures will reduce the period when temperature restricts plant growth and animal production. Tropical grasses such as the widely adapted *Heteropogon contortus* are sensitive to both low temperatures and frost, and hence the above climate changes could increase the opportunities for plant growth if moisture and nutrients are available. Similarly, the life cycles of plants and animals which are temperature and/or frost sensitive are likely to be affected by these climatic trends with potential impacts on plant (e.g. crown rust on oats, McKeon and Howden 1993) and animal productivity (e.g. buffalo fly, Sutherst 1990).

Pasture species vary considerably in their response to temperature (Fitzpatrick and Nix 1970, Sweeney and Hopkinson 1975, Christie 1975). When expressed as temperature indices, i.e. proportion of maximum growth, various groupings have been found, e.g. C_3 and C_4 species (Fig. 7). Although the individual species of a native pasture sward can have different responses to temperature (e.g. McKeon *et al.* 1990), a general 'C_4' native pasture relationship (McCown 1980-81) has proved useful in modelling the temperature effect on sward growth and animal production.

Modelling studies have demonstrated that combining indices of simulated soil water, solar radiation and temperature in the form of a growth index (Fitzpatrick and Nix 1970) explains a large proportion (50-80%) of year-to-year variability in seasonal (three monthly) plant growth and animal production (McKeon *et al.* 1980). In Part II (Hall *et al.* 1998) we show that the length of the growing season (percentage of days when growth index >0.05) accounts for approximately 50% of the year-to-year variation in steer liveweight gain at three locations in coastal Queensland at low stocking rates. Using both length of the growing season and the percentage of pasture eaten (utilisation) accounts for approximately 70% of the variation in all available liveweight gain data. Although May (Fig. 4) and winter warming since the 1980s would be expected to increase the length of the growing season, variation in rainfall has dominated this effect (Fig. 8). The small decline in length of growing season for the coastal sub-zone, which approaches conventional statistical significance at P=0.063, is heavily influenced by the first five years of the record (1891-96). Removal of this period results in no trend.

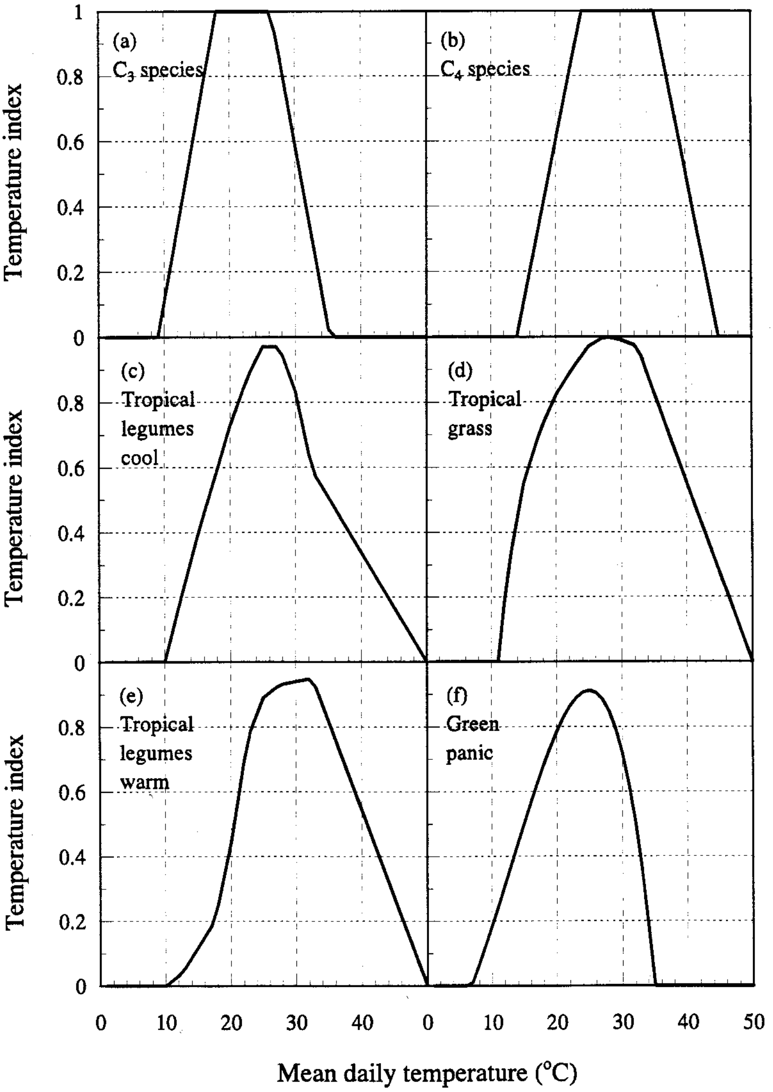


Fig. 7. Temperature indices (proportion of maximum growth) for different pasture species grouping:

a) adapted from Fitzpatrick and Nix (1970);
b) C_4 native pasture sward adapted from McCown (1980-81);
c) adapted from Sweeney and Hopkinson (1975);
d) adapted from Sweeney and Hopkinson (1975);
e) adapted from Sweeney and Hopkinson (1975);
f) green panic from Ivory and Whiteman (1978) calculated assuming day-time and night-time temperature were mean temperature ± 6.7°C respectively.

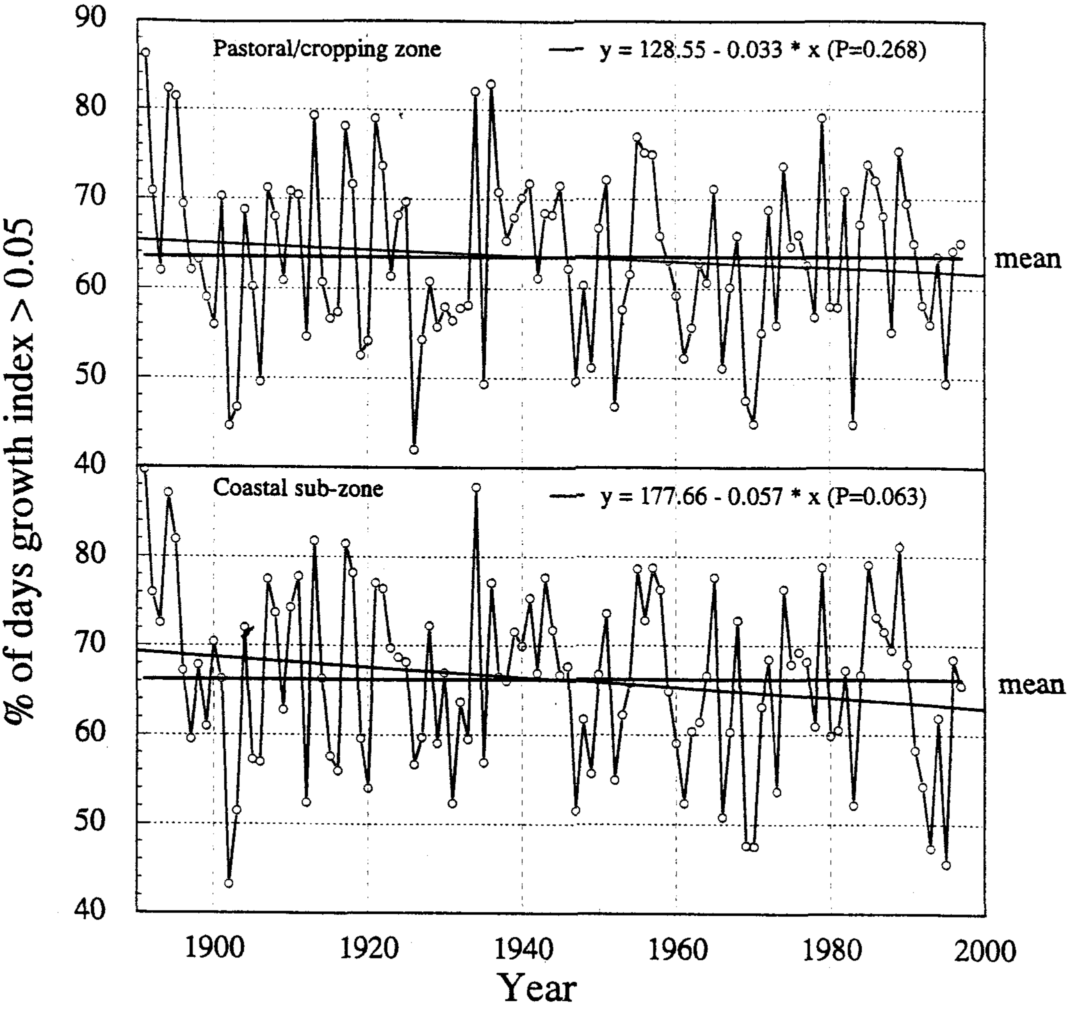


Fig. 8. Length of the growing season as measured by the percentage of days when the simulated growth index exceeded the threshold value of 0.05 (Hall *et al.* 1998) for Queensland's pastoral/cropping zone and coastal sub-zone.

Studies of the different effect of night and day temperature on tropical grass growth have shown that low night temperatures greatly reduce growth (e.g. green panic, Ivory and Whiteman 1978). Hence, when temperature limits growth, the impact of a warming in minimum temperature would be expected to be more important than a rise in maximum temperature. The trends in May temperature indices (Fig. 9) for various species or plant types show significant ($P<0.01$) increases of 26 to 92% from 1957 to 1996. The year 1958 is a major warm anomaly in both the fitted surface data set and the data of Torok and Nicholls (1996). The high maximum and minimum temperatures in 1958 result in the highest temperature indices in most cases for the 40-year period and this event highlights the difficulty of distinguishing between trends and variability. Nevertheless, the above analysis suggests that the increasing trend in May temperatures could potentially contribute to pasture growth and animal production if moisture and nutrients (nitrogen) are available.

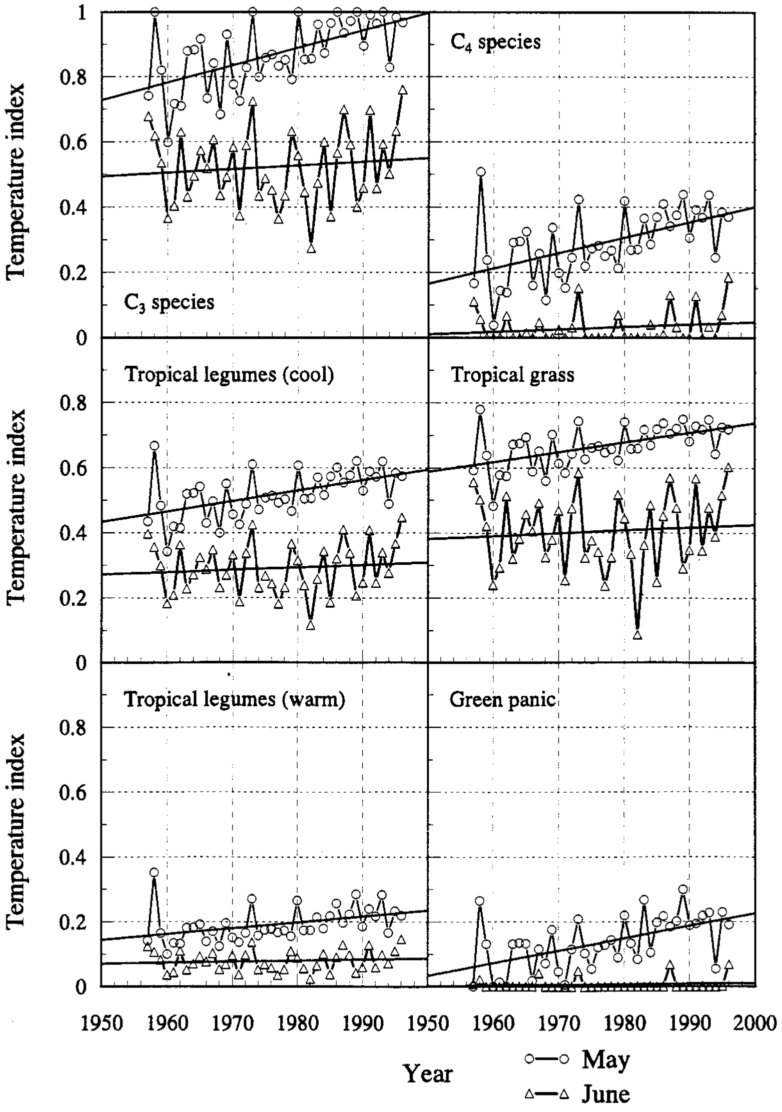


Fig. 9. Time-series of calculated temperature indices for different species groups for May and June.

Stability of relationship between El Niño-Southern Oscillation and climate of Queensland's grazing lands

The impact of future climate change is uncertain due to the wide range of possible options for managing future greenhouse gas emissions and the uncertainty of modelling the effect of an enhanced greenhouse effect on regional climates such as Queensland's grazing lands. Given such uncertainty, it has been hypothesised (McKeon *et al.* 1993) that grazing and agricultural management may be able to adapt in part by using current skills in seasonal forecasting based on the SOI. Thus examination of the stability of correlations between SOI and rainfall is an important component of monitoring climate change.

McKeon *et al.* (1998) have reported analyses of times series of rainfall, standard deviation of rainfall (cube root transformation), SOI, standard deviation of SOI, and correlation coefficients of SOI and rainfall (cube root transformation) for different seasonal durations: calendar year, ENSO year (April-March), summer and winter. Moving windows with different time frames were used: 19, 22, 30 and 40 years. In addition they analysed specific examples used in seasonal forecasting for agricultural management (Hammer *et al.* 1991): August to October SOI with November to March rainfall; and May SOI minus February SOI with June to October rainfall. We present a summary of the major findings relevant to climate change.

Analysis using a 19-year moving window showed large fluctuations in mean rainfall, standard deviation and correlation with the SOI (Fig. 10). The period ending in the 1940s had low summer and annual rainfall, and low simultaneous correlation with SOI. These findings are supported by Allan *et al.* (1996b) who analysed global sea surface temperatures and atmospheric pressures in twenty-year blocks suggesting 'coherent fluctuations in major elements of the ocean-atmosphere system over the period of historical instrumental record. In particular the 1921-1941 epoch stands out as one in which ENSO and the climate system appear to have been functioning in a less robust manner than in recent or earlier periods over the last 120 or so years'.

The short-term window (19 years) show important recent 'trends' with decline in annual SOI. The 19-year annual mean for 1977 to 1996 has been four units below the long-term mean of zero (Fig. 10). However, the 19-year mean annual rainfall is still above that of the 1930s-40s supporting Nicholls *et al.* (1996) analysis who found an increase in base line mean rainfall once the effect of SOI was removed. Similarly, the 19-year mean winter rainfall has been above the long-term mean (~10%), and the standard deviation is also higher whilst the 19-year mean winter SOI is three to four units below the mean. Trenberth and Hoar (1997) tested updated SOI data to mid-1997 using a regression model with autoregressive moving average (ARMA) errors and showed that the mean SOI for the post-1976 period was statistically ($P<0.05$) different from the overall mean. Trenberth and Hoar (1997) concluded 'that the tendency for more El Niño and fewer La Niña events since the late 1970s is highly unusual and very unlikely to be accounted for solely by natural variability'. Alternatively, recent joint analyses of global patterns of ocean temperatures and atmospheric pressure over the last 124 years indicate that there are a number of significant quasi-periodic decadal to secular scale signals in the climate system. These analyses show that the behaviour of El Niño since 1976 is not linked to the secular global warming trend but to oscillatory signals operating around 20-40 and 60-80 year periods (R.J. Allan, pers. comm.).

The stability of forecasting seasonal rainfall was evaluated over the last 100 years for two examples (Charters Towers and Goondiwindi, Table 2). Probabilities of winter rainfall (June to October) at Goondiwindi vary depending on direction of SOI (rising or falling) during previous months of April and May (Stone *et al.* 1996a). The chance of success from 'betting' on receiving less or more than median rainfall depending on the SOI phase has remained relatively constant for the three 33-year periods considered. However, the period 1961 to 1993 had significantly (<0.05) more rising phases (14) than falling phases (2). In contrast the probability of summer rainfall (November to March) at Charters Towers varies depending on the value of SOI from August to October (McKeon *et al.* 1990, Clewett *et al.* 1991). The chance of success from 'betting' on less or more than median rainfall varies between the three periods and is similar to the overall global behaviour of the ENSO phenomenon (Allan *et al.* 1996b). The recent period (1961 to 1993) with a high success rate (84%) has included major droughts associated with strongly negative SOI periods and highlights the need to monitor the links between ENSO and rainfall in this region. For example, it is now known that the anomalous wet period of the early 1970s was associated with several La Niña events, and hence should not bias expectations of long-term rainfall or carrying capacity (McKeon *et al.* 1990).

The example of rainfall at Charters Towers also highlights the dangers in evaluating seasonal forecasting systems. Periods of limited success (1928-60), or high success (1961-93), are likely to lead to either missed 'opportunities' during periods of stronger ENSO links with rainfall, or too high an expectation of success. A more mechanistic understanding as provided by GCMs (Suppiah *et al.* 1998) of these varying relationships is clearly required to take maximum advantage of this type of seasonal forecasting.

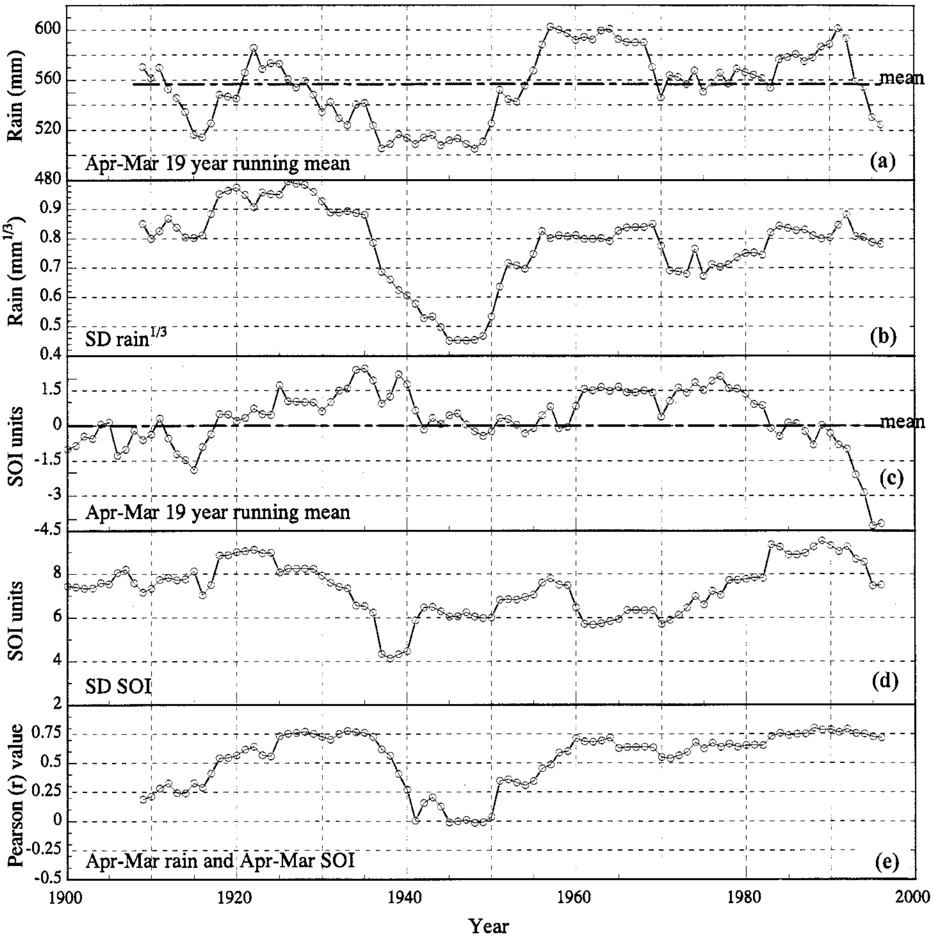


Fig. 10. Moving 19-year periods for Queensland's pastoral/cropping zone: a) moving average of April - March rainfall; b) moving standard deviation (calculated using 'n-1') of April - March rainfall (cube root transformation); c) moving average of April - March SOI; (d) moving standard deviation of April - March SOI; and e) moving Pearson correlation of April - March SOI and April - March rainfall (cube root transformation).

The stability of SOI-rainfall correlations for Queensland has been investigated with GCM simulations for 2xCO_2 (Suppiah *et al.* 1998). Existing correlations were found to continue to occur under these conditions of global warming although there was a tendency for more rainfall to be simulated for a given SOI value at 2xCO_2. Similar trends have been occurring on a continental scale since 1973 (Nicholls *et al.* 1996). Thus statistical seasonal forecasting systems will require regular revision but are still likely to provide useful information for agricultural decision making.

Table 2. Performance of two forecasting examples over the last 100 years:

A. June to October rainfall at Goondiwindi using SOI phase for April to May calculated by AUSTRALIAN RAINMAN (i.e. not the original phase system of Stone and Auliciems 1992);

B. November to March rainfall at Charters Towers using lag SOI for August to October.

A 'success' refers to a successful 'bet' that:

1) at Goondiwindi, rainfall would be less than the median for SOI falling phase, and that rainfall would be greater than or equal to median for SOI rising phase; and
2) at Charters Towers, rainfall would be less than median for SOI ≤ -5, and rainfall greater than or equal to median for SOI ≥ +5.

A.	**Goondiwindi rainfall (June – October)**							
Period	**Years**	**SOI April – May**				**'Bets'**	**Success**	**% Success**
		Falling		**Rising**				
		<195 mm	**≥ 195 mm**	**<195 mm**	**≥ 195 mm**			
1895-1927	33	4	2	2	5	13	9	69
1928-1960	33	8	3	3	4	18	12	67
1961-1993	33	1	1	5	9	16	10	63
1895-1993	99	13	6	10	18	47	31	66
% chance of ≥ median rainfall		68	32	36	64			

B.	**Charters Towers rainfall (November - March)**							
Period	**Years**	**SOI August - October**				**'Bets'**	**Success**	**% Success**
		≤ -5		**≥ +5**				
		< 482 mm	**≥ 482 mm**	**< 482 mm**	**≥ 482 mm**			
1895-1927	33	10	4	2	6	22	16	73
1928-1960	33	4	5	3	7	19	11	58
1961-1993	33	9	1	2	7	19	16	84
1895-1993	99	23	10	7	20	60	43	72
% chance of ≥ median rainfall		70	30	26	74			

The fluctuations and trends described above raise a number of issues for agricultural policy and management.

1) There is a need for statistical analyses to discriminate trends from natural variability. There is a great risk that managers/governments will have to take action (e.g. allocation of funds under Drought Exceptional Circumstances) in response to the fluctuations/trends without an up-to-date statistical analysis, and an appreciation of the limitations of statistical methods available.

2) Most current seasonal forecast systems use all available data (typically over 100 years) without removal of trends. Clients (such as policy makers, farmers and graziers) who may be ignorant or sceptical of the possibility of global warming trends are unlikely to demand such a de-trended analysis and will be prepared to accept probability distributions derived from the last 100 years. We have found that the concepts involved in probabilities are as difficult to communicate as the uncertainties of separating current trends from inter-decadal variability. Given the infancy of extension of seasonal forecasting systems, e.g. RAINMAN (Clewett *et al.* 1994) was only released in 1991, a conservative approach has been adopted in dealing with the effect of possible trends in rainfall or frost frequency when constructing seasonal probabilities, i.e. the trends are ignored.

However, if the public is made aware of only one aspect of climate (e.g. ENSO), then incorrect perceptions of the relationships between forcings and seasonal climate are possible. For example, it would be understandable that a grazier might conclude, from the immediate experience of the 1990s, that negative SOI periods were associated with warmer than average winters rather than colder winters as indicated by analysis of the last 100 years (Hammer *et al.* 1991).

Global warming in the 21st Century

Rangeland management has to consider both previously recorded climatic possibilities (Isdale *et al.* 1998) and the probability of future climatic change resulting from global warming. The increasing atmospheric concentrations of greenhouse gases and possible future increases in CO_2 emissions in the next 100 years have formed the basis for calculation of climatic scenarios for the 21st century (CIG 1992, 1996). These scenarios are based on a sound scientific understanding of climate processes and are calculated using a variety of GCMs. However, CIG (1996) cautions '.... uncertainty surrounding future greenhouse gas and sulfate emissions, shortcomings in climate modelling, and difficulties in determining regional patterns of climate change from global estimates mean that predictions of future climate change at a regional level still cannot be made'. Nevertheless, the scenarios provide examples of 'plausible futures' and suggest that substantial changes in rainfall and temperature are possible.

For example, CIG (1996) reported temperature and rainfall responses calculated from different GCMs (with slab or coupled ocean models) for a high emission scenario (doubling CO_2 in 2070) and a high climate sensitivity (4.5°C for $2xCO_2$). The 'high scenario for 2070' (CIG 1996) suggests a possible change of ±10% in eastern Australia summer rainfall calculated from coupled GCMs whilst a response of 0 to +20% was calculated from slab GCMs. To put these scenarios in perspective, McKeon *et al.* (1998) analysed 30-year moving means of summer and winter rainfall since 1890 for Queensland's grazing lands. For summer (October-March) rainfall, 30-year moving means ranged from 10% below the 107-year mean (365 mm, 1919-48) to 13% above the 107-year mean (460 mm, 1949-78). For winter (April-September) rainfall, 30-year moving means ranged from 10% below the 107-year mean (135 mm, 1921-50 and 1951-1980) and 5% above the mean (158 mm, 1892-1921 and 156 mm, 1961-90).

The ±10% changes for eastern Australia from the coupled model are similar to the extremes of 30-year rainfall experienced in the last 107 years for the smaller region of Queensland's grazing lands. The upper boundary of +20% calculated from slab GCMs would be double the deviation of any 30-year period in the last 100 years from the long-term mean. However, from an alternative view point, the change in summer rainfall from the period 1921-49 to the period 1950-79 was +26% (460/365mm), similar in magnitude to possible changes simulated by slab GCMs.

The range for winter rainfall response was -20% to 0% for coupled GCMs and -10% to 0% for slab GCMs. The magnitudes of greatest possible decline (i.e. -20% and -10% for coupled and slab GCMs respectively) are substantially greater than the maximum deviation of any 30-year period from the long-term mean over the last 100 years (-10% to +5%). However, they are similar to the 15% decline in rainfall experienced from the period 1892-1921 to the following 30-year period, 1922-51 (135/158mm).

Whilst the possible changes in summer rainfall (-10% to +10%) appear to be of the same magnitude as experienced in 30-year rainfall over the past 100 years, the key issue for grazing management is the change in variability, especially in the sequence of wet and dry years. The 30-year period with lowest 30-year mean rainfall (1919-48) also had the lowest year-to-year variation whilst the period with highest 30-year mean rainfall (1949-78) included the widespread drought period of the 1960s (Fig. 1a,b). Thus, in terms of grazing management and degradation processes, general changes in climate averages may disguise important variation at yearly and decadal time scales. A more formal analysis of GCM output data using seasonal or shorter time steps will be required to evaluate these scenarios in terms of impact on possible land degradation.

Conclusions

Policies on management of 'natural systems' are responding to the knowledge that global climate forcings are changing, e.g. increased radiative forcing due to increasing greenhouse gas concentration resulting from human activities (Hughes and Westoby 1994). Rather than accepting the consequences of climatic variability or change as 'natural', humans will have to take a more pro-active stance to manage the grazing resource and conserve biodiversity given that climate changes may occur faster than agricultural systems or natural ecosystems can adapt (Hughes and Westoby 1994).

In this paper we have documented significant trends in the climate of Queensland's grazing lands. Large changes/fluctuations are occurring in the behaviour of ENSO and minimum temperatures are increasing although the causes are yet to be identified. The capacity of GCMs to represent phenomenon such as ENSO appears to be improving and such models may allow simulation of possible mechanisms in the near future (Suppiah *et al.* 1998). The use of GCMs in both seasonal forecasting and uncovering the causes of the above trends may develop greater confidence in their capabilities and eventually result in the adoption of GCM projections of future climate in the planning of rangeland use.

Major issues for Queensland's grazing lands are the impact of the 1990-95 ENSO events on rainfall, and ENSO behaviour since 1976. At the time of writing climatologists are still debating the role of natural variability in contrast to the possible links to global warming. The continued monitoring of these trends/fluctuations and climatological debate will be important for the future management of Queensland's grazing lands.

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