NORTH CENTRAL VICTORIAN CLIMATE: PAST, PRESENT AND FUTURE

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North central Victoria has experienced significant natural climate change over the past 20 000 years. At the height of the last ice age, the region was colder by 5°C or more with uplands and slopes under subalpine vegetation. Modern vegetation patterns were not established until the early Holocene. The first half of the Holocene was wetter than today, while the second half was affected by a less stable climate influenced by a strengthening El Niño–Southern Oscillation. Climate immediately prior to European occupation may have been wetter than during the historical period. Thus the pre-European climate and land surface influences on regional water balance may have been different to that which is generally assumed. Climate during the historical period was statistically homogenous, but with drier and wetter periods. Modest warming began in the mid 20th century, by about 0.4°C per century from 1950 to 1996. From 1997, maximum temperature has undergone a significant upward step change ($p<0.01$) of 0.9°C. Rainfall has decreased by 19%, with May–October rainfall undergoing a significant ($p=0.05$) downward step change from 2000. Maximum temperature is now non-stationary with respect to rainfall and is experiencing an upward trend consistent with climate model projections. These changes are equal to or greater than those projected for 2030, and are significantly affecting agriculture and forestry, ecosystems, fire risk and water resources. Evidence from pre-historic, historic and model projections of future climate for this region suggest that climate change can often be abrupt, with 'stable' periods showing considerable decadal variability. Prudent risk management would treat the post 1996 climate as the new baseline and plan for further changes.

Key words: climate change, climate variability, palaeoclimate, Victoria

North central Victoria is situated on the northern slopes of the Great Dividing Range, although in that region the range is not so great; the altitude of the highest point is Mt Macedon at just over 1000 m, with low points of the divide to the east and west reaching below 400 m and 600 m respectively. The region is warm temperate with a pronounced seasonal cycle. In the south, average monthly temperature ranges from 5–17°C with an annual average of 8°C; in the north, it ranges from 9–22°C with an annual average of 16°C. Rainfall is winter-dominant across the whole region, annual totals ranging from over 1200 mm in the south-west corner to about 400 mm in the north. Seasonal proportions are similar across the region suggesting that the climatic influences on rainfall are consistent, with topography being the major determinant of the north to south increasing gradient.

Physiography and climate are linked in north central Victoria, which has provided a bridge between north–south and east–west over periods of past climate change. Clues as to this behaviour can be seen in similar ground flora of the grassland and grassy woodland vegetation communities, and of mallee-whipstick vegetation in similar climates on the north-facing slopes north of Bendigo and the south-facing slopes of low-rainfall areas north-west of Melbourne. During cool climates the Divide would also have linked the eastern and western highlands, and relicts of cool climate flora occur throughout the region.

Climate can therefore be used to integrate the dynamic history of the region. Past climates need to be interpreted over a wider area than the region itself, partly due to the lack of local palaeoclimatic data. Limited evidence from climate proxies is due to poor environmental preservation combined with little in-depth investigation of potential proxies. Instrumental climate observations commenced in the latter half of the 19th century, and at the beginning of the 21st, climate records are showing early but strong signs of an enhanced greenhouse climate signal. This paper discusses recent climate shifts in the light of our scientific understanding of past and future climate, concluding that human-induced climate change is already occurring much more strongly than anticipated.

PAST CLIMATE

The region has a number of key features that have formed under the influence of climate. They include:

- The deep lead system of buried Tertiary sediments, in most cases following ancestral routes of current rivers,
- The low flow regimes of the modern river system,
- Large quantities of cyclic salts stored in soils and groundwater systems.

Climate interactions with these systems all have important consequences for the future of natural resources within the region.

The pre-European environment was strongly influenced by the last glacial cycle peaking at about 20 000 BP and Holocene climate, and by the response of the environment and ecological systems to those changes. Humans have occupied the region for over 30 000 years, based on dates at Lake Tyrrell in Victoria (32 000 BP; Richards et al. 2007), Lake Mungo in New South Wales (40 000 BP; Bowler et al. 2003) and Tasmania (35 000 BP; Cosgrove 1995). Aboriginal peoples' influence on the environment was strong, especially influencing the extent of grassy ecosystems through the use of fire.

Pollen analysis from lowland sites from eastern highlands approximately 150 km east of the region show that at the height of the last ice-age, about 20 000 BP the vegetation was dominated by alpine taxa (McKenzie 2002). In the same study lower elevation sites (c. 250–900 m) had alpine communities, subalpine woodland and chenopod steppe occurring to 12 000 BP. Alpine taxa were absent from the lowest site at Buxton from 12 000 BP, successively disappearing from more elevated sites, showing a major decline at 1177 m between 8900 and 7500 BP (McKenzie 2002). Although these sites are wetter than north central Victoria, the major climatic control at this time was temperature. Slightly warmer sea surface temperatures of 1–2°C near Tasmania (McKinnon et al. 2004) but lower sea levels, suggest cooler continental conditions at this time. This is consistent with insolation-driven warming occurring in the northern hemisphere, transferring into the southern hemisphere through ocean warming, with lagged warming on land. McKenzie (2002) suggests that mean annual temperatures in the late Pleistocene were several degrees lower then today – the current gradient over 1200 m of about 7°C indicates that the late glacial may have been at least that much colder, if the vegetation is any guide, or colder if the lapse rate was higher (note that lower atmospheric CO_2 may have also played a part in the reduced presence of woody vegetation under drier and colder conditions). She also suggests the peak of rainforest expansion occurred at about 6000 BP, though the role of temperature is unclear. Moros et al. (2009) show that during the early Holocene the oceans south of Victoria were under the influence of weather systems now closer to the equator, a higher equator to pole temperature gradient, and more intense westerlies.

The evidence for a wetter period across the region between about 7000 and 5500 BP is clear, with the western Victorian maar lakes overflowing (Jones et al. 1998) wetter conditions further west at Lake Tyrrell (Luly 1993) extending to Lake Eyre (Magee et al. 1995). Drying continued from that time, with increasing evidence of unstable hydroclimatic conditions, reaching its driest point between 3000 and 2000 BP. The onset of this phase appears to be associated with widespread evidence for the onset of the El Niño–Southern Oscillation (ENSO) phenomenon (Woodroffe et al. 2003; Vargas et al. 2006; Donders et al. 2008). In southern Victoria, lake levels show a degree of recovery, until about 650 BP, where drier and perhaps warmer conditions ensued. However, the largest regional climate event of the past two millennia occurred in about 1840[1], when the lakes in southern Victoria began a long-term decline that has been ascribed to natural climate change (Jones et al. 2001).

HISTORICAL CLIMATE

Although there are sporadic climate observations from the 1840s, regular observations in Melbourne from 1855 and records from regional Victoria not long afterwards, the only existing homogenous data set linking the earliest observations to modern climate was that constructed by Jones et al. (2001) for the area around Camperdown-Terang in western Victoria. The Bureau of Meteorology (BoM) has concentrated on modern records, especially those taken after the amalgamations of the colonial weather services into the BoM in 1908. No effort will be made constructing or assessing similar records for central Victoria because a major project is underway to do this for the whole region[2].

[1] Years before present (BP) set by radiocarbon dating and similar methods is conventionally set at 1950 AD. Years BP are noted whereas years AD are given by number only.

[2] http://www.pages-igbp.org/science/last2millennia.html

Instead, the 20th century climate will be concentrated on for the following reasons:

- The climate record for western Victoria from the mid 19th century suggests that the relationship between the major climate variables is stationary (Jones 1995).
- Regional homogeneity between different variables means that if a major change occurs in a measured variable (e.g., rainfall, temperature, sunshine hours), it will occur over a wide area. For these three variables, the spatial extent of homogeneity is sunshine hours/radiation, temperature and rainfall from largest to smallest.

Twentieth century climate is explored through gridded spatial data provided by the BoM Australian rainfall and surface temperature portal that is based on all Australian rainfall data and the high quality temperature data (Della-Marta et al. 2004). The region explored is 143.5°–145.5°E and 35.5°–37.5°S, which extends from just north of Melbourne slightly across the New South Wales border. Annual data for rainfall dates from 1900, whereas temperature data dates from 1950 due to limitations on digitised daily data. These data sets are slightly different, but the differences are small and do not alter the analysis' conclusions. Analysis of linear and non-linear (rapid shifts) behaviour is undertaken, the former using least squares linear analysis and the latter using the bivariate analysis (Maronna & Yohai 1978). Long-term high quality records in the region are rare. Maryborough is the only high quality temperature record (Della-Marta et al. 2004) and appears to be affected by urbanisation (and is flagged as urban by the Bureau of Meteorology). High quality rainfall stations (Lavery et al. 1997) are in the west of the region, Beaufort, Coonooer Bridge and Canary Island, Yarroweyah to the north, with no stations to the south on the northern slopes. The closest high quality pan evaporation station (Jovanovic et al. 2008) is Eildon, but homogeneity tests reveal problems with bird guard adjustments before 1982. Therefore, gridded data is preferred for analysis but has shorter availability for rainfall and temperature than individual records.

The statistical tools used for analysing and communicating current climate change processes are generally those designed for measuring a signal/noise construct from a stationary baseline, and adaptation to climate change has been interpreted on this basis (Hulme & Brown 1998; Risbey et al. 1999; Kane & Yohe 2000). Although this distinction may be useful for attribution of cause, it is not suitable for planning adaptation, which requires a whole of climate approach (Hall 1999; Jones 2004). If climate consists of stationarity, oscillations, trends and potentially irreversible shifts in state, then the assessment of ongoing and potential future risks will require a larger set of tools than in common use.

In the first instance, this requires the diagnosis of both abrupt and trending behaviour in climate records to distinguish between short-term variability under stationary conditions, gradual change and rapid shifts in climate variables. The bivariate test has been used widely in climatology for assessing inhomogeneities and shifts in time series of climate variables (Potter 1981; Bücher & Dessens 1991). Shifts are tested by comparing a subject time series with a homogenous reference series of random numbers (after Vivès & Jones 2005). If artificial inhomogeneities and immediate local effects can be ruled out, the principle of regional homogeneity suggests that such shifts are due to a shift in climate. If a causal mechanism within the broader climate system can be attributed, then a climatically-induced step change has occurred.

Maximum and minimum temperatures (Tmax, Tmin) over the region have behaved differently so will be analysed separately (Fig. 1). Each was examined for step changes first before being subject to trend analysis. Annual rainfall (P) tested for the period 1900–2009 experienced a roughly 25% chance of having a random shift in 2001, which is not statistically significant. Autumn only shows a shift to the 25% level in 1990, much less than in other regions such as southern Victoria and south-easterm Australia that have been tested. Taking the months where persistent decreases have occurred – March to October – the change is significant to the 5% level in 2001 (Table 1).

Tmax shows a statistically significant shift of +0.9°C that has a <1% chance of being random after 1996. Tmin is statistically homogenous. Therefore, when assessed for trend for 1950–1996, Tmax shows a warming trend of 0.3°C per century, but over the whole period shows a trend of 1.8°C per century. Tmin shows a trend of 0.5°C per century, so for the past decade the two records have been changing independently of each other. For the state, rainfall shows a shift in annual rainfall at the 10% level from 1996. Tmax and Tmin records are longer from this source dating back to 1910. The shift in Tmax remain significant from 1996, but Tmin also shows an upward shift from 1958 of 0.5°C at the <1% level. The post-1950 trends in the regional and state records compared

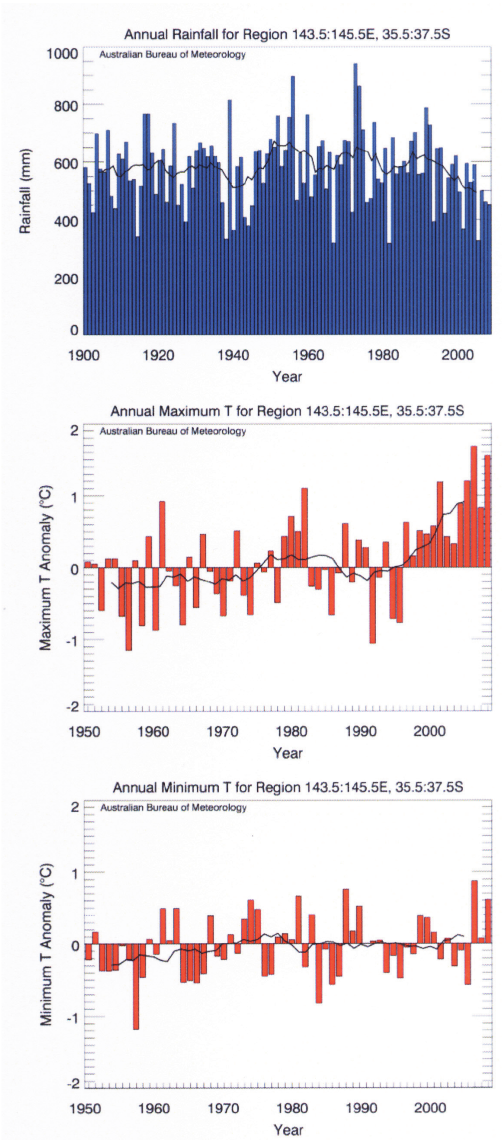

Fig. 1. Gridded annual total rainfall (1900–2009) and annual average maximum and minimum temperatures (1950–2009) for north central Victoria.

show a difference of 0.1°C for Tmax, whereas Tmin has been warming at twice the rate over the state as a whole. This is most likely due to rainfall reductions having a greater effect on Tmin away from the coast through reductions in cloud cover and night-time radiation of heat. There was a cooling trend in both Tmax and Tmin in the state average from 1910 until 1958, perhaps influenced by an increasing trend in P, consistent with Nicholls et al.'s (2004) findings for New South Wales.

Attribution of shifts

Tmax and rainfall are inversely correlated at a range of timescales from daily to multiple years (Workneh & Rush 2002; Nicholls et al, 2004). Coughlan (1979) found strong correlations between annual P and Tmax over most of Australia except for coastal areas and northern Australia. Using the high quality data sets of the BoM, Power et al. (1998) found significant correlations between annual average Tmax and total P across most of Australia, which waned in some coastal areas and disappeared on offshore islands. They also noted that the relationship between Tmax and P changed during the early 1970s, after which Tmax was higher for a constant value of P. This, they linked to a simultaneous change in the Southern Oscillation Index (SOI). By removing co-dependency between Tmax and Tmin, they found that Tmin was also linked to higher rainfall totals. A further analysis using a climate model forced by sea surface temperatures showed that Tmax and P are cohesively linked over most areas from 40°N–40°S except for North Africa (Power et al. 1998).

Based on this evidence, the working hypothesis is that during episodes of natural variability, rainfall and maximum temperature are quasi-stationary, subject to changes in variables such as ENSO (Power et al. 1998; Nicholls et al. 2004). Therefore, a step change in natural variability will see correlated variables change together, with perhaps a level of drift affected by trends in variables such as the SOI. Externally forced changes may introduce non-stationary behaviour between correlated variables that exhibit step changes similar to those observed in climate model output.

This is illustrated by extending Nicholls et al.'s (2004) analysis of annual average P and Tmax from New South Wales by using the bivariate test to detect shifts in the high quality data sets. Annual rainfall in New South Wales 1910–2009 experienced

Table 1. Results of the bivariate test carried out on rainfall (1900–2009) and maximum and minimum temperature anomaly (anomaly from 1961–1990, total period 1950–2009) for north central Victoria. Also shown is the relationship between maximum temperature and rainfall, and state-wide averages (1900–2009 for rainfall, 1910–2009 for temperature). Ti_0 is the bivariate test statistic in the year prior to the step change.

	Average	Std Dev	Ti_0	p|0	Year	Shift
Rainfall (mm)						
Annual	580	126	6.6	0.25	2000	-112
Summer	112	46	Homogenous			
Autumn	136	59	7.6	0.25	1990	-40
Winter	173	47	Homogenous			
Spring	159	59	Homogenous			
Mar-Oct	422	103	10.2	0.05	2001	-113
Temperature (°C)						
Tmax		0.6	21.4	0.01	1996	0.9
Tmin			Homogenous			
Other						
Tmax/P (°C)		0.6	20.5	0.01	1998	0.9
P Victoria (mm)	646	116	8.0	0.10	1996	-97
Tmax Victoria (°C)		0.6	24.3	0.01	1996	0.9
Tmin Victoria (°C)		0.5	34.9	0.01	1958	0.5

a step change in 1947 of $p{\sim}0.05$, increasing by 65 mm within a long-term average of 519 mm. Tmax shows no significant step change at that time, but does decrease as rainfall increases as expected. Tmax shows an upward shift in 2001 of 1.1°C at $p<0.01$. Joint Tmax/P reference testing shows a step change in 1997, consistent with the rest of SE Australia, and P/Tmax reference shows a non-significant shift in 1947 ($p>0.10$). Therefore, the earlier event is (quasi)-stationary and the later is non-stationary. Analysing other area averages shows significant Tmax/P shifts of $p<0.01$ in south-eastern Australia and the Murray-Darling Basin in 1997, and in south-western Western Australia in 1994.

Average regional P for north central Victoria shows no significant shifts prior to 2001, although Vivès & Jones (2005) found statistically significant upward shifts in 1946 using individual station records. Tmax was regressed linearly against P from 1950–1996, the period of statistical homogeneity, and the cumulative residuals plotted. They show that Tmax clearly diverges from 1997. Power et al. (1998) calculated the residual of Tmin and P as influenced by linear regression with Tmax, showing that both are highly correlated, so are in phase. This suggests that Tmax has become highly non-stationary with regard to P and Tmin, whereas the two latter variables are still closely linked. The cumulative sums of the residuals for Tmax calculated from P, Tmin and P calculated from Tmax are shown in Fig. 2. They show that Tmax/P has deviated from its historical range of ±2°C to almost -8°C, Tmin/Tmax is still within its historical range and P/Tmax is only just exceeding its historical range, having all been in phase from before 1970 to 1996.

The relationship between P and Tmax was further investigated using output from six climate models from the PCMDI data base for a grid square centred on the south-eastern corner of the region (Fig. 3). They were forced by radiative changes following historical patterns to 2000, and the Special Report for Emission Scenarios (SRES; Nakiçenovic & Swart 2000) marker scenario A1B to 2100. These results show a similar pattern to the observations, where a period of stationary climate is followed by an abrupt departure of Tmax from the anti-phase relationship it has with P. In all cases, Tmax shifts by the year 2000, whereas changes in P are much more variable.The GISS model shows no shifts, P and Tmax change at the same time in the MIROC model and P changes 23 years after Tmax in the CSIRO Mark3.0 model.

Kearney et al. (2010) investigated increases in mean temperature from multiple ensemble runs from four global climate models for the Melbourne Region, concluding that the local warming rate of 1.4°C per century was very likely to be due to anthropogenic warming. The rate of change in this analysis is closer to 1.2°C per century but the bivariate analysis

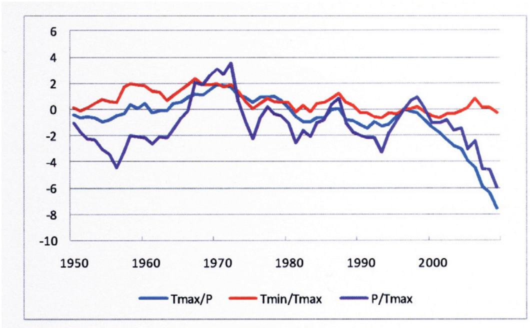

Fig. 2. The cumulative sums of the residuals for Tmax calculated from P (Tmax/P), Tmin (Tmin/Tmax) and P (P/Tmax) calculated from Tmax. The vertical axis is in °C for T and standard anomalies for P.

suggests that about two-thirds of that trend can be attributed to the rapid shift in T max of 0.9°C, with a sympathetic increase of 0.8°C in Tmin in the months November to February and an average decrease of 0.2°C between March–October, the months in which rainfall declined.

Therefore, Tmax in north central Victoria is changing due to climate change, while the influences on rainfall and Tmin are less clear, although there is a small upward trend in Tmin. Whether there is an anthropogenic signal affecting rainfall is more difficult to assess. The most substantive work on this has been carried out by the South-East Australian Climate Initiative (SEACI)[3]. The influences on south-eastern Australian rainfall are mainly seasonal and are influenced by a range of large-scale climatic influences including ENSO, the Southern Annular Mode (SAM) and the Indian Ocean Dipole (IOD) (Murphy & Timbal 2008; Shi et al. 2008; Ummenhofer et al. 2009). Air pressure also forms one of the strongest links with rainfall, particularly autumn, which has the lowest predictability but has experienced the largest reductions (Timbal & Murphy 2007).

The current dry period is estimated to have started in October 1996 (Bureau of Meteorology 2006) but bivariate test analyses and findings from other assessments show that a variety of influences are affecting different seasons (e.g. Nicholls 2010). For example, the November–February period in north central Victoria decreases by a negligible 5 mm after 1996, but the rainfall decrease south of the ranges around Melbourne is year round (Jones 2009), suggesting that the Great Dividing Range is a barrier to summer rainfall coming from the north. Timbal (2009) also notes that the evolution of the dry period has changed with the three driest years of 2006–2008 intensifying and broadening the dry period into the early winter and spring. These three years are associated with consecutive occurrences of a positive IOD, not historically unprecedented, but occurring within an increasing trend of IOD events that have been attributed to anthropogenic climate change (Cai et al. 2009).

The Southern Annular Mode (SAM) has also been implicated in winter drying as increasing positivity drives westerly rain-bearing systems further polewards (Timbal et al. 2008; Nicholls 2010). However, positive modes of SAM, associated with lower autumn–early winter rainfall, have been increasing since the 1970s, not matching the timing of the autumn decrease (Timbal et al. 2008). The trend in SAM also involves increasing air pressure over Australia, also associated with decreasing rainfall (Timbal et al. 2008). The sub-tropical ridge (STR) constitutes another link between air pressure and rainfall (Drosdowsky 2005). Based on current statistical relationships, the STR has been linked to the 70% of the decline in south-eastern Australian rainfall to 2006 (Timbal et al. 2008, 2010). Central pressure of the STR and mean global warming have been increasing in close correspondence with each other (Timbal et al. 2008, 2010) and may also be linked to declines in both south-east and south-western Australia (Hope et al. 2009).

The influence of tropical sea surface temperatures that comprise the ENSO and IOD phenomena on the decadal variability of winter-spring rainfall is apparent for most of the 20th century (Timbal 2009; Nicholls 2010), but does not appear to be associated with the latest declines (Timbal et al. 2010). Natural variability in the winter-spring period is also very low, so may be being suppressed, but is high in autumn. Rainfall changes therefore appear to be linked to anthropogenic influences through the increasing intensity of the subtropical ridge, possible increasing frequency of positive IOD events (e.g. 2006–2008) and a potential change of influence in other teleconnections (e.g. ENSO; Timbal et al. 2010). Summer rainfall is increasing over much of the continent (Smith 2004) and its most southerly incursions are maintaining summer rainfall in the study area.

[3] http://www.seaci.org/index.html

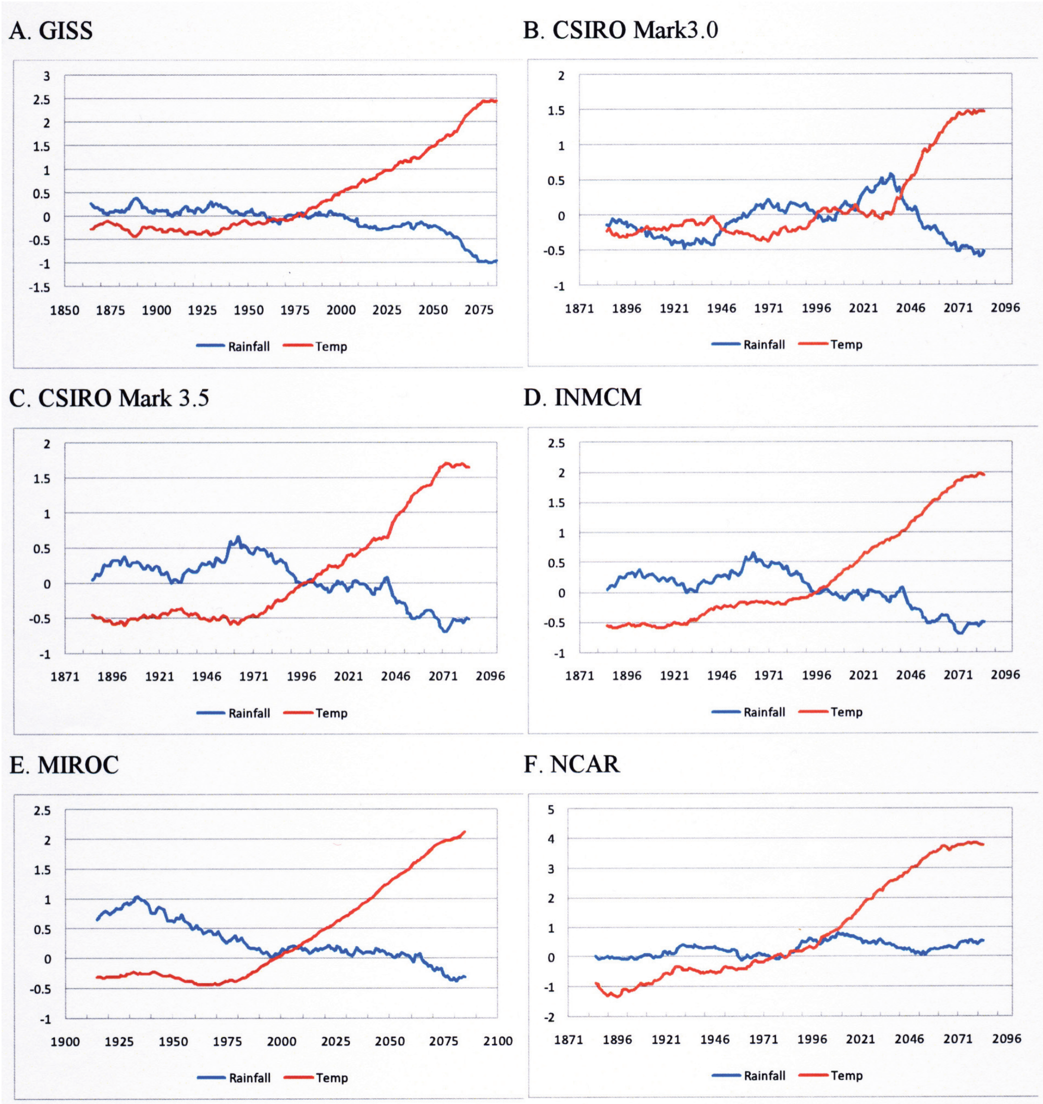

Fig. 3. Thirty-year running means of standard anomalies (1961–1990) for rainfall and temperature from six climate models forced with the SRES A1B emission scenario for the grid square corresponding to 37°S and 145.75°E.

IMPACTS

As documented in other papers from this meeting and in recent papers and reports, regional systems are responding to average changes or extremes associated with P and Tmax change or to variables that are closely linked to these, especially humidity and potential evaporation. However, direct attribution is more difficult. The following brief descriptions summarise some of these changes and responses.

Food and fibre

Only a few studies of regional agriculture, horticulture and forestry make direct attribution to climate change, but many more studies are documenting responses to changing conditions where climate is a significant factor. Plantation forestry is being affected by longer dry periods, fires and economic effects of the global financial downturn, making management more expensive, increasing risk and reducing market opportunities (Stewart 2009). The phenology of tree and vine crops is responding to warmer conditions with ripening of grapes occurring 3–4 weeks earlier from 1998 than previously experienced (L. Webb pers. comm.). Research is currently underway to attribute this change.

The agricultural sector is undertaking significant adaptation responses to drier and hotter conditions although capacity depends greatly on factors such as farm size, access to technology and secondary income sources (Thwaites et al. 2008). Large changes to irrigation water supply since the reduction in rainfall began has led to wholesale changes in the dairy industry sustained by irrigated pasture, increases in irrigation water prices and significant reductions in yield (Jones 2010). Recently the majority of irrigators in Campaspe irrigation district voted to leave irrigation *en masse* after zero allocations in the past four years out of five (Northern Victoria Irrigation Renewal Project 2010).

Ecosystems

The failure of flowering in Box-Ironbark forests in five of eight years since 2001 was linked to a collapse in populations of woodland and forest bird species after the third drought episode from a series of surveys to 2008 (Mac Nally et al. 2009a). Proportions of declines were similar irrespective of foraging or nesting guild, broad habitat tolerances, or whether or not species had been classified previously as being of conservation concern. The largest extant areas of native vegetation including national parks were as greatly affected as mostly cleared agricultural landscapes. The baseline for the key flowering species, Red Ironbark *Eucalyptus tricarpa*, for Rushworth Forest from 1947–1970 was a failure rate of every 12.5 years (Keatley & Hudson 2007), whereas since 1997 the failure rate for the whole region has been every 2.75 years (Mac Nally et al. 2009a).

Population declines in frogs since 1980 are associated with reductions of available water for breeding in wetlands due to prolonged drought conditions (Mac Nally et al. 2009b). Wetlands across the region are at risk from the warmer and drier conditions affecting their ecology, degrading water quality and other ecosystem services (Jin et al. 2009). Changes in phenology of species occurring throughout the region have also been linked to drying and warming conditions including breeding times of the critically endangered Helmeted Honeyeater *Lichenostomus melanops cassidix* (Chambers et al. 2008) and the common brown butterfly *Heteronympha merope* (Kearney et al. 2010).

Fire Risk

The risk of catastrophic fires throughout the region has also increased, with the events of Black Saturday, 7 February 2009, reversing the long-running decline in fatalities from wildfire within the state of Victoria. Fires in north central Victoria included a fire west of Bendigo that burnt 330 ha, killed one person and destroyed 58 houses and the Redesdale fire south of Bendigo that burnt 9500 ha and destroyed 7 houses (Teague et al. 2009). Other serious fires in the region were south of Bendigo the Kilmore-Murrundindi fire complex in the south-east corner and Bullarto fire in the south-west, the latter on February 23–25. While extreme, the more northern fires did not exceed previous experience, although the Bendigo fire travelled two to three times faster than later simulated by a fire behaviour model, presumably due to higher wind speeds (Sullivan & McCaw 2009).

The worst conditions occurred in south central Victoria. The antecedent conditions were ascribed to prolonged drought, extreme seasonal conditions and the desiccation of wet sclerophyll forests that led to fuel increasing the intensity of the fire front. In evidence to the Royal Commission the fire index was between two and three times greater than Black Friday 1939 and significantly worse than Ash Wednesday 1983 (Tolhurst 2009). This refers to the Macarthur forest fire danger index (FFDI) that was standardised at 100 for the 1939 Black Friday fires (Lucas 2009). The FFDI peaked at 140 at Bendigo Airport and Redesdale (Sullivan & McCaw 2009). Pyrocumulus clouds increased the severity of the fires, through heat released by condensation, resulted in lightning strikes and moving the fires further eastward than they otherwise would have moved (Teague et al. 2009).

Lucas (2009) has calculated a data set of FFDI for Australia from 1972–3 to 2009–10 and includes the Bendigo station. Wind speed measurements used in calculating the FFDI were problematic before 1991, so were homogenised using the bivariate test to assess step changes in the record, then those records adjusted in a stepwise manner to be homogenous with the instrumental wind record from 1993. The mean for the whole period is 79 days of high fire danger above per year but the mean changes from 63 to 107 before and after the 1995–96 fire year. The change is statistically significant to the <1% level using the bivariate, F- and t-tests.

Water Resources

Urban, domestic and irrigation water supplies, including those of the major regional storage Lake Eppalock, have been at record low levels (Russell & Long 2008). Draw-downs from Lake Eppalock were made in anticipation of returns to normal inflows, a gamble that did not pay off. The loss of a reliable regional water supply has led to the establishment of the Goldfields Water Pipeline.

Cartwright and Simmonds (2008) suggested that historical clearing is likely to have a greater impact on groundwater resources than projected climate change, but the evidence of a sharp decline since 1996 from bores within the region (Reid et al. 2008), and anecdotal evidence of permanent streams and springs changing to ephemeral status or drying altogether related to the author suggest that the opposite may be the case. Despite potential benefits to dryland salinity, modelling within the region suggests that reduced streamflow volume is likely to contribute to higher in-stream salinity (Austin et al. 2010).

PROJECTED FUTURE CLIMATE

Climate projections have been made available for all the catchment management areas (CMAs), including the North Central CMA (Table 2). The ranges of projected change cover 80% of the confidence range and are developed from the latest version of regional projections from Australia (CSIRO and BoM 2007; DSE 2008). These summarise the changes in mean conditions projected by up to 23 climate models (depending on the variable), essentially capturing the signal of mean anthropogenic climate change, but omitting the potential variability, or noise. This is done because the state of the science currently means that decadal variability, especially on the regional scale, is unpredictable. These changes were projected for individual emission scenarios, with the SRES B1 comprising a low change, A1B, a medium change and A1FI, a high change (Table 2; Nakiçenovic & Swart 2000).

The evidence presented in this paper shows that climate in north central Victoria has shifted more rapidly than anticipated, but in the same direction as in Table 2. The evidence of the shift becomes the most important information for planning adaptation, suggesting that climate has already changed and further change may build on that. Therefore, model projections need to be integrated with these latest changes in some way. Attribution of the nature of changes will assist in this task. One particularly important issue is how much of the rainfall change may be due to decadal variability and therefore may return to wetter conditions in future. The notion that the changes are a random short-term departure from 'normal' can be discounted for purposes of risk management, although never totally (this is a scientific rather than practical aspect of uncertainty).

Accordingly, many of the impacts projected for future warmer and drier conditions, especially for those projected in 2030, will be happening now, if the impact assessments are accurate. This includes changes to wetland communities (Nielsen & Brock 2009), increased fire risk (Lucas et al. 2007), reductions in water supply (Jones & Durack 2005), and a range of other impacts (summarised by Hennessy et al. 2007). Monitoring of changes will be essential to assess the accuracy of impact models but also to observe and understand adaptive responses.

CONCLUSIONS

The long-term history of north central Victoria shows that climate has been a considerable driver of change over thousands of years. Based on a transect across similar altitudes east of the region, during the last ice age about 20 000 BP, alpine flora may have dominated at least the southern part of the region above several hundred metres altitude (McKenzie 2002). Warming in the years following suggests that by the time that climate had ameliorated in western Victoria below 200 m (Jones et al. 1998), the tree-line was still rising to just over 1000 m about 9000 BP further east (McKenzie 2002), i.e. the height of Mount Macedon. This suggests a process of warming through 5°C or more, increasing rainfall and re-afforestation into the Holocene; trees moved from dwarf forms in sub-alpine heath and/or from ice-age refugia in sheltered valleys across the landscape. This process took thousands of years, which suggests that although ecosystems show great resilience to large changes, they may also take a long time to respond fully.

People were undoubtedly living in this landscape during the whole period. Important resources, such as greenstone from the Heathcote axis were widely traded (McBryde & Watchman 1976). The grasslands

Table 2. Annual and seasonal median estimates and ranges of change for north central Victoria for the SRES A1B (2030) and B1 (2070 low) and A1FI (2070 high) emission scenarios for a range of climate variables (DSE 2008).

		2030		2070			
		Medium emissions		Low emissions		High emissions	
ANNUAL		Median	Range	Median	Range	Median	Range
Average temperature	°C	0.9	0.6 to 1.2	1.4	1.0 to 2.0	2.8	1.9 to 3.9
Average rainfall	%	-4	-9 to 1	-6	-14 to 2	-11	-26 to 4
Potential evaporation	%	2	0 to 5	4	1 to 8	8	2 to 15
Wind speed	%	0	-5 to 4	0	-9 to 7	-1	-17 to 13
Relative humidity	%	-0.7	-1.5 to -0.1	-1.2	-2.4 to -0.1	-2.3	-4.7 to -0.2
Solar radiation	%	0.7	0 to 1.6	1.1	0 to 2.6	2.2	0.1 to 5.1
SPRING							
Average temperature	°C	0.9	0.6 to 1.3	1.5	1.0 to 2.1	2.9	1.9 to 4.2
Average rainfall	%	-7	-17 to 1	-11	-26 to 2	-20	-44 to 3
Potential evaporation	%	2	-1 to 5	3	-2 to 8	5	-3 to 15
Wind speed	%	0	-7 to 6	0	-12 to 10	-1	-24 to 20
Relative humidity	%	-1.1	-1.9 to -0.2	-1.8	-3.5 to -0.4	-3.5	-6.8 to -0.8
Solar radiation	%	1.0	0.1 to 2.2	1.7	0.1 to 3.7	3.3	0.3 to 7.2
SUMMER							
Average temperature	°C	1.0	0.6 to 1.4	1.6	1.1 to 2.3	3.1	2.0 to 4.5
Average rainfall	%	-1	-11 to 10	-2	-18 to 16	-4	-32 to 31
Potential evaporation	%	2	0 to 5	3	0 to 8	7	0 to 15
Wind speed	%	1	-6 to 6	1	-9 to 10	2	-18 to 19
Relative humidity	%	-0.6	-1.8 to 0.3	-1	-2.6 to 0.4	-2	-5.1 to 0.8
Solar radiation	%	0.3	-0.4 to 1.2	0.6	-0.7 to 2.0	1.1	-1.4 to 3.8
AUTUMN							
Average temperature	°C	0.8	0.6 to 1.2	1.4	0.9 to 2.1	2.7	1.8 to 4.0
Average rainfall	%	-1	-9 to 6	-2	-14 to 10	-4	-26 to 20
Potential evaporation	%	3	2 to 6	6	3 to 10	11	5 to 19
Wind speed	%	-2	-9 to 4	-4	-16 to 6	-7	-30 to 12
Relative humidity	%	-0.5	-1.6 to 0.5	-0.9	-2.6 to 0.8	-1.7	-5.1 to 1.5
Solar radiation	%	0.3	-0.6 to 1.5	0.6	-1 to 2.5	1.1	-1.9 to 4.8
WINTER							
Average temperature	°C	0.7	0.5 to 1.0	1.2	0.8 to 1.7	2.2	1.5 to 3.3
Average rainfall	%	-4	-14 to 2	-7	-18 to 3	-13	-32 to 6
Potential evaporation	%	7	0 to 17	11	0 to 28	22	0 to 54
Wind speed	%	0	-6 to 5	0	-9 to 9	1	-18 to 17
Relative humidity	%	-0.5	-2.2 to 0.3	-0.8	-2.9 to 0.5	-1.6	-5.7 to 0.9
Solar radiation	%	1.7	-0.4 to 4.3	2.8	-0.7 to 7.2	5.3	-1.3 to 13.9

and grassy woodlands that provided rich pickings for early graziers were maintained by fire, as shown by the increase in the number of trees and shrubs that occurred through much of this landscape when frequent fire was removed. Human interactions during the prehistorical period, would therefore have helped shape the landscape, but did not heavily use its resources beyond that which could sustain the population.

The period of European occupation of the region has seen great pressure placed on the natural resources of the region, which have all been heavily exploited: the forests during the gold rush to fuel steam power; the gold itself, which contributed to Marvellous Melbourne; the soils for grazing, leading to widespread soil loss and erosion, reversed through the time of the Soil Conservation Authority; the Box-Ironbark forests for fencing and fuel-wood through-out the 20th century. In many cases, this leads to pre-existing vulnerabilities that have been exacerbated by drier and hotter conditions. However, some advantage may have been gained for dryland salinity with reduced saline water tables in specific locations.

The historical climate may have been different to the pre-European climate, but insufficient evidence exists to confirm whether the wetter conditions that maintained full crater lakes in Western Victoria extended north over the Great Dividing Range. High levels occurred in Lake George near the ACT from ~600 to 300 BP, but the evidence over broader south-eastern Australia indicates generally dry conditions over the last four millennia (Fitzsimmons & Barrows 2010) except for southernmost Victoria, which was wetter from about 1800 BP to 1840 (Jones et al. 2001). It remains unclear as to whether wetter conditions in southern Victoria and the ACT in the centuries prior to the historical period were linked, implying wetter conditions across north central Victoria, or whether they were influenced by rainfall from the south and the north respectively. This change in conditions has implications for how water balance of the pre-European landscape is contrasted with historical water balance and the hydrological response to widespread vegetation clearing.

Victoria's historical climate demonstrates statistical homogeneity from the 19th to the 20th century (Jones 1995). Large variations in rainfall were reflected by similar movements in rainfall and temperature, where rainfall is correlated with minimum temperature and inversely correlated with maximum temperature. While there is some warming of both Tmax and Tmin since the mid 20th century, the relationship between rainfall and Tmin in north central Victoria remains statistically homogenous whereas the relationship between P and Tmax is not.

Drier and warmer conditions since 1996 mark a statistically significant shift in the relationship between Tmax and P. Analysis of the output from six climate models covering a similar geographic region suggests this is common under enhanced greenhouse warming. Changes to rainfall are more complex, with the largest decline in autumn. In north central Victoria, the only aspect of rainfall that undergoes a statistically significant shift (to the 5% level) is the March-October period. Given that the annual shift across the whole of Victoria in 1996 is -15% at p=0.10 compared to -19% in 2000 at p=0.25, the lack of significance is most likely due to a higher coefficient of variability in the north central region.

This is equivalent to shifting Bendigo most of the way to Rochester, or Maryborough north of St Arnaud, based on comparison to 1961–1990 averages. Based on the model projections of Tmax and P in Fig. 3, rainfall could potentially be quite variable in future, moving up or down, but Tmax is likely to continue increasing subject to the mitigation of climate change via greenhouse gas reduction. Prudent risk management will adjust the climate baseline to reference the past 13 years but further warming in the future is very likely and drying over the long-term is likely, though shorter term upward fluctuations are also possible. Given the changes cascading through natural and human systems in the region from recent shifts in climate, the potential for further change presents a substantial challenge.

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