Sub 584

03/06/03

Submission to the Select Committee on the Recent Australian Bushfires

Professor David Karoly
School of Meteorology
University of Oklahoma

Dr James Risbey
School of Mathematical Sciences
Monash University

Summary

We submit that the extreme climatic conditions during 2002 and early 2003 were a major factor in the severity of the recent Australian bushfires. These extreme conditions were due to a drought associated with an El Niño event, together with record high temperatures. These extreme high temperatures very likely cannot be explained by natural climate variability alone. They are part of a warming trend in the Australian region over the last 50 years associated with increasing greenhouse gases in the atmosphere. Hence, greenhouse climate change is likely to have been a significant factor increasing the severity of the bushfires. Urgent action needs to be taken to reduce greenhouse gas emissions into the atmosphere, as greenhouse climate change is expected to produce increasingly more severe fire danger conditions in Australia.

Background

Our submission focuses on one of the terms of reference:
(b) the causes and risk factors contributing to the impact and severity of the bushfires,
and the overall goal of the Committee "to identify measures that can be implemented by governments, industry and the community to minimise the incidence of, and impact of bushfires on life, property and the environment."

We submit that the extreme climate conditions during 2002 and early 2003 were one of the major factors in the severity of the recent Australian bushfires. It is our view that, while the bushfire emergency was largely the result of a range of natural and human factors, the Committee needs to consider the impact that the extreme climatic conditions had on the severity of the 2002 bushfire season.

The probability of extreme fire danger in Australia increases during droughts associated with El Niño events (Williams and Karoly, 1999). This is due to the higher temperatures, drier conditions and reduced humidity at these times.

The reports of the Intergovernmental Panel on Climate Change (IPCC) are the collective work of thousands of scientists charged with advising Governments and the World Meteorological Organization about the science of climate change. The recent assessment of climate change by the IPCC (2001) concluded that "global average surface temperatures have increased over the 20th century by about 0.6°C" and "most of the observed warming over the last 50 years is likely to have been due b the increase in greenhouse gas concentrations".

Estimates of confidence in observed and projected changes in extreme weather and climate events (from IPCC 2001 Summary for Policymakers Table 1)

Confidence in observed changes (latter half of the 20th century)	**Changes in phenomena**	**Confidence in projected changes (during the 21st century)**
Likely	**Higher maximum temperatures and more hot days over nearly all land areas**	Very likely
Likely, in a few areas	**Increased summer continental drying and associated risk of drought**	Likely, over most continental interiors

As noted in the table above, the IPCC assessment reported that hotter, drier conditions are likely during the 21st century, which would lead to increased risk of extreme fire danger. Recent related research (Williams et al, 2001) has shown that Australia is likely to have substantial increases in fire danger associated with greenhouse climate change, due to the higher temperatures and reduced soil moisture.

The 2002/2003 fire season

Our research (Karoly et al., 2003a, 2003b) has found that Australia, and the Murray-Darling Basin in particular, had record low rainfall and record high maximum temperatures during March-November 2002. The severe drought and record temperatures during 2002 caused record evaporation rates and drying of vegetation in parts of Australia. We believe that it is highly probable that this extreme dryness also affected the ACT and created the tinderbox conditions that made the fire season so severe.

It is important for the Committee to note that our research has found that the severity of the 2002 conditions was not simply a result of natural variations of climate. By looking at other droughts as our baseline, we found that the severity of the 2002 drought was a result of record high temperatures that added to the speed and extent of evaporation from the soil and vegetation. These much higher than average temperatures are part of a warming trend across Australia over the last 50 years. It is very likely that this warming trend cannot be explained by natural variability alone. Instead, our research has found that these high temperatures are consistent with a global warming trend that has been attributed to human-induced emissions of greenhouse gases. We have shown that the warming in the Australian region over the last 50 years is likely to be due to the increase in greenhouse gases. (Karoly, 2003).

The reduced rainfall in 2002/2003 was associated with an El Niño event and natural climatic variability in the Australian region. While higher temperatures are also associated with droughts, the record high temperatures in 2002 are much higher than for other drought years and very likely cannot be explained by natural climate variability alone. These record high temperatures can best be explained by greenhouse warming in the Australian region superimposed on climate variations associated with El Niño.

We submit that climatic conditions during bushfire seasons will continue to increase in severity until global warming can be slowed. For this reason, it is crucial that the Committee consider the relative importance of the climatic conditions on the emergency. It is also important that the Committee consider that future strategies to ameliorate the impact of bushfires may need to include actions to prevent the continuation of the causes of global warming, such as reducing emissions of greenhouse gases.

References

IPCC (2001) *Climate Change 2001: The Scientific Basis*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., et al., (eds.)]. Cambridge University Press, .

Karoly, D. (2003) Detection of anthropogenic climate change in the Australian region. *7th Intl. Conf. on Meteorology and Oceanography of the Southern Hemisphere*, Wellington, NZ, 24-28 March 2003.

Karoly, D., J. Risbey and A. Reynolds (2003a) *Global warming contributes to Australia's worst drought*. WWF Australia, 8pp (available from www.wwf.org.au).

Karoly, D., J. Risbey, A. Reynolds, and K. Braganza (2003b) Global warming contributes to Australia's worst drought. *Australasian Science*, April 2003 issue.

Williams, A. A. J., and D. J. Karoly (1999) Extreme fire weather in Australia and the impact of the El Nino-Southern Oscillation. *Aust. Met. Mag.*, **48**, 15-22.

Williams, A.A.J., D.J. Karoly and N. Tapper (2001) The sensitivity of Australian fire danger to climate change. *Climatic Change*, **49**, 171-191.

Contact details:

Both authors are happy to be interviewed by the Committee either in person or by telephone.

Prof David Karoly, School of Meteorology, University of Oklahoma,
100 E Boyd St, Norman OK 73019, USA
ph: +1-405-325 6446, fax: +1-405-325-7689, email: dkaroly@ou.edu
(Will be in Australia during 2 June – 10 July 2003, visiting Dr Risbey.)

Dr James Risbey, School of Mathematical Sciences, Monash University
Box 28M, Clayton, VIC 3800, Australia
ph: (03) 9905 4461, fax: (03) 9905 5020, email: james.risbey@sci.maths.monash.edu.au

GLOBAL WARMING CONTRIBUTES TO AUSTRALIA'S WORST DROUGHT

CLIMATE CHANGE

Professor David Karoly[1], Dr James Risbey[2], and Anna Reynolds[3]

14 January 2003

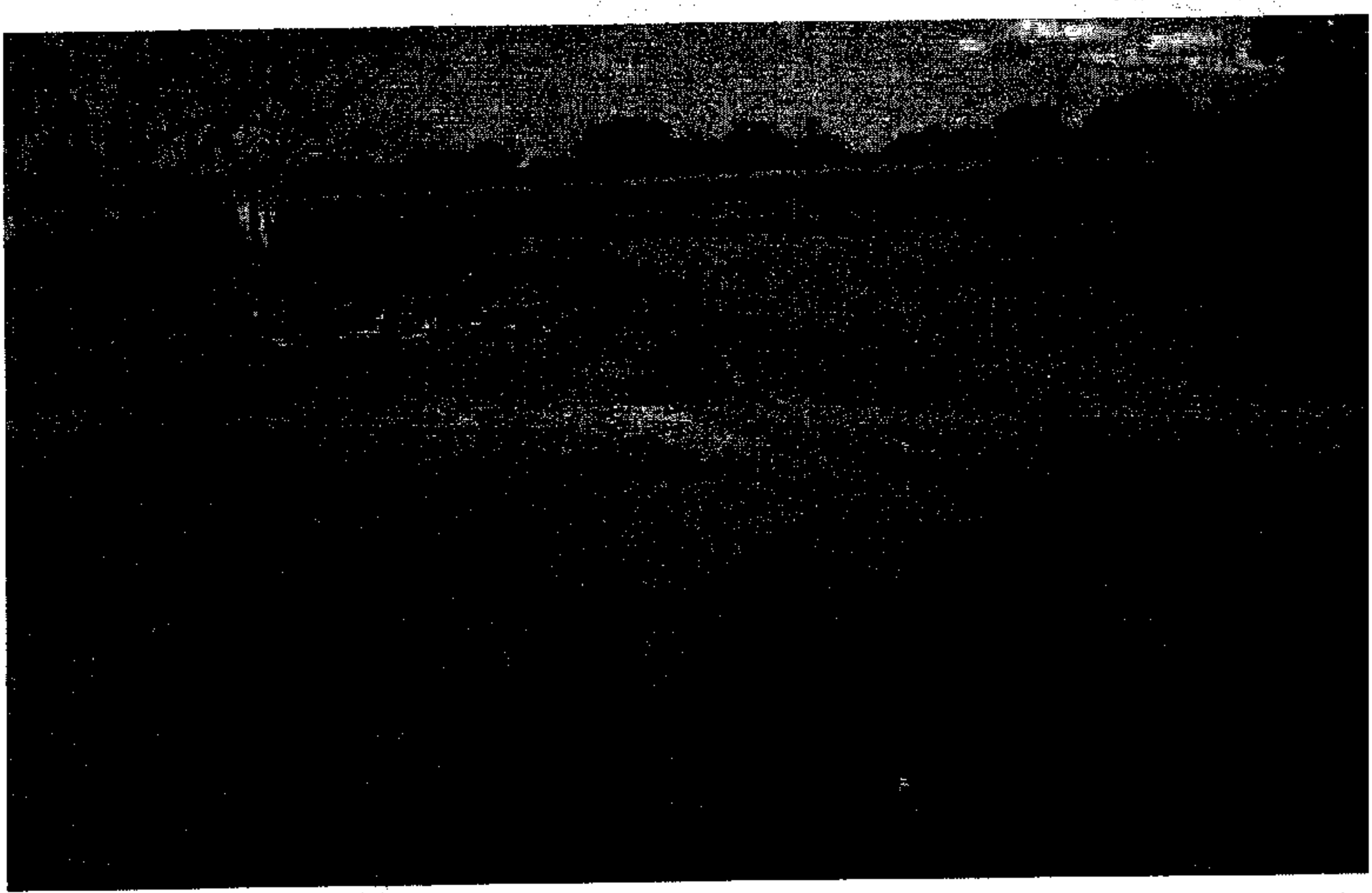
[1] School of Meteorology, University of Oklahoma, Norman, OK.USA. Previously at Monash Uni.
[2] Centre for Dynamical Meteorology and Oceanography, School of Mathematical Sciences, Monash University, Clayton, VIC
[3] WWF Australia, Sydney, NSW

New research has found that human-induced global warming is a key reason why the Australian drought of 2002 has been so severe.

OVERVIEW

During 2002, Australia experienced its worst drought since reliable records began in 1910. The average Australian rainfall for the 9 months March-November 2002 was the lowest ever during this period. The drought was concentrated in eastern Australia with the Murray-Darling Basin, the nation's agricultural heartland, receiving its lowest ever March-November rainfall in 2002.

This drought has had a more severe impact than any other drought since at least 1950, because the temperatures in 2002 have also been significantly higher than in other drought years (see Table 1 and 2). The higher temperatures caused a marked increase in evaporation rates, which sped up the loss of soil moisture and the drying of vegetation and watercourses. This is the first drought in Australia where the impact of human-induced global warming can be clearly observed.



GLOBAL WARMING CONTRIBUTES TO AUSTRALIA'S WORST DROUGHT

THE 2002 DROUGHT – HIGHER TEMPERATURES THAN ANY PREVIOUS DROUGHT

Australia experienced its lowest March-November[4] rainfall for more than 50 years in 2002, less than 50% of normal, as much of the country was gripped by severe drought (see Figure 1).

The drought was associated with El Niño, the irregular warming of the equatorial Pacific Ocean that occurs about once every three to seven years. Most major Australian droughts over the last 100 years are associated with El Niño (Nicholls 1983, 1985).

In 2002, Australia also recorded its highest-ever average annual daytime maximum temperatures following a warming trend that has intensified over the past two decades. The temperature across Australia was 1.6°C higher than the long-term average and 0.8°C higher than the previous record.

While higher temperatures are expected during El Niño triggered droughts (Jones and Trewin 2000), the 2002 drought temperatures are extraordinary when compared to the five major droughts since 1950, with average maximum temperatures more than 1.0°C higher than these other droughts (see Table 1).

Figure 1:
Profile of the 2002 drought

Average rainfall anomalies in March-November 2002 shown as deciles. Decile 1 (red) indicates rainfall amounts that are very much below average and have occurred in less than one year in ten. From the Bureau of Meteorology

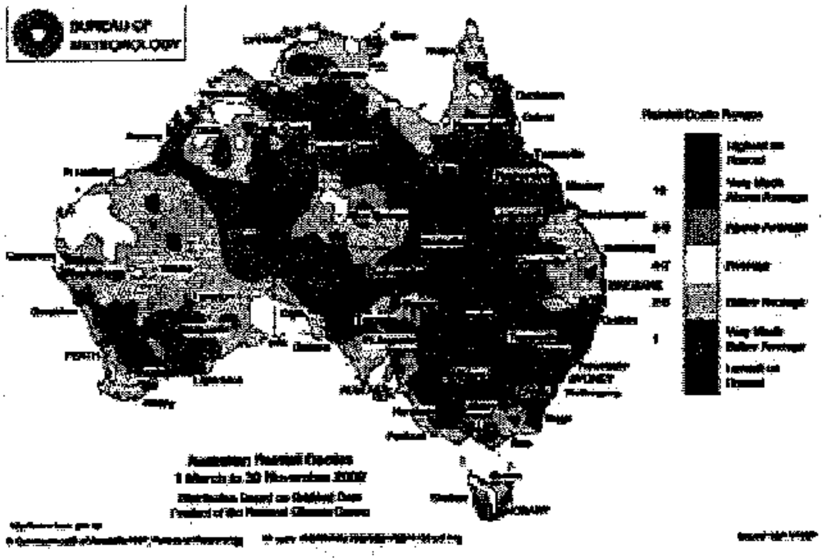


Table 1:
The 2002 drought compared to other droughts since 1950

Year	Rainfall (mm/month)	Maximum temperature anomaly (°C)
2002	**14.1**	**1.65°C higher than average**
1994	16.5	0.69°C higher than average
1982	22.4	0.12°C higher than average
1965	25.0	0.24°C higher than average
1957	21.8	0.50°C higher than average

Average conditions over Australia for the 9 months March-November of major drought years since 1950. Shown are the average monthly rainfall and the average daily maximum temperature anomalies (relative to the 1961-1990 long-term average of 29.1 mm/month and 26.6°C). Data from the Bureau of Meteorology.

---

[4] *March-November rainfall has been used, rather than the calendar year, as droughts are often more intense in this period, when there is a stronger influence from El Niño.*

GLOBAL WARMING CONTRIBUTES TO AUSTRALIA'S WORST DROUGHT

HIGHER TEMPERATURES IN THE MURRAY DARLING INTENSIFY THE DROUGHT'S IMPACT

The Murray-Darling Basin was at the centre of the Australian drought in 2002.

The basin received its lowest ever March-November rainfall in 2002, only 45% of normal rainfall. This key agricultural region makes up one-seventh of the total area of Australia and 75% of NSW. The Basin, that produces 40% of Australia's agricultural product, covers towns north to Toowoomba, west to Broken Hill and south to Victoria and South Australia.

During 2002, the Murray-Darling Basin experienced average maximum temperatures more than 1.2°C higher than in any previous drought since 1950 (Table 2). The higher temperatures led to greater evaporation of water, exacerbating the drought. Higher evaporation rates make it difficult to sow crops, place existing crops under stress, and take water from rivers and reservoirs. The higher maximum temperatures and drier conditions have also created greater bushfire danger than in previous droughts (Williams, Karoly, and Tapper 2001).

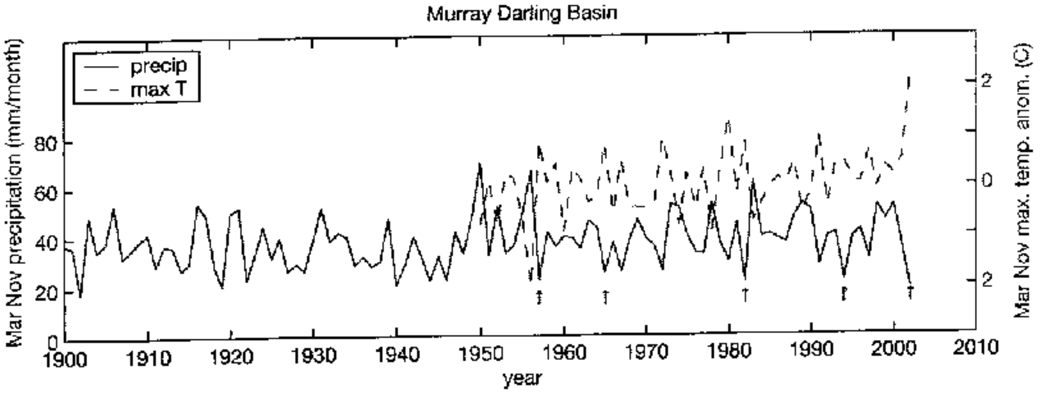
Table 2:
The 2002 drought in the Murray-Darling Basin compared with other droughts

Year	Rainfall (mm/month)	Maximum temperature anomaly (°C)
2002	**18.3**	**2.14°C higher than average**
1994	21.8	0.48°C higher than average
1982	21.2	0.87°C higher than average
1965	25.2	0.83°C higher than average
1957	22.5	0.89°C higher than average

Average conditions in the Murray Darling Basin for the 9 months March-November of major drought years since 1950. Shown are the average monthly rainfall and the average daily maximum temperature anomalies (relative to the 1961-1990 long-term average). Data from the Bureau of Meteorology

Figure 2:
Drought severity in the Murray Darling is increasing with global warming

The time series in Figure 2 shows that each drought is associated with higher maximum temperatures, but 2002 was extraordinary because of the record high temperatures.



Interannual variations of March-November average monthly rainfall (solid blue line) and average daily maximum temperature (dashed red line) for the Murray-Darling Basin. Small arrows indicate the 5 major drought years; 1957, 1965, 1982, 1994, and 2002, since 1950.

GLOBAL WARMING CONTRIBUTES TO AUSTRALIA'S WORST DROUGHT

WHY HUMAN-INDUCED GLOBAL WARMING INCREASED THE SEVERITY OF THE 2002 DROUGHT

The drought in 2002 was due to natural climate variations associated with El Niño. However, the higher temperatures this year are not attributable to the natural variations of Australian climate alone.

The higher temperatures in this year's drought are part of the overall warming trend in Australian temperatures over the last 50 years (Figure 3). Australian average surface temperature increased by more than 0.7°C between 1950 and 2001.

In 2001, the Intergovernmental Panel on Climate Change concluded *"most of the observed (global) warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations"* (IPCC 2001). The warming trend over the last 50 years in Australia also cannot be explained by natural climate variability and most of this warming is likely due to the increase in greenhouse gases in the atmosphere (Figure 4, Karoly 2001). This figure shows that the actual trend in Australian temperatures since 1950 is now matching the climate models of how temperatures respond to increased greenhouse gases in the atmosphere. These greenhouse gas increases occurring today are due to human activity; burning fossil fuels for electricity and transport, and land clearing.

Figure 3.
Warming trend in Australia

Trends in average daily maximum temperature over Australia over the period 1950-2001.

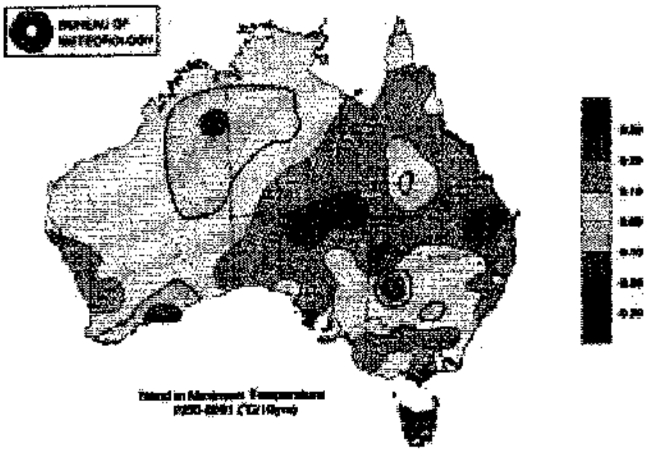
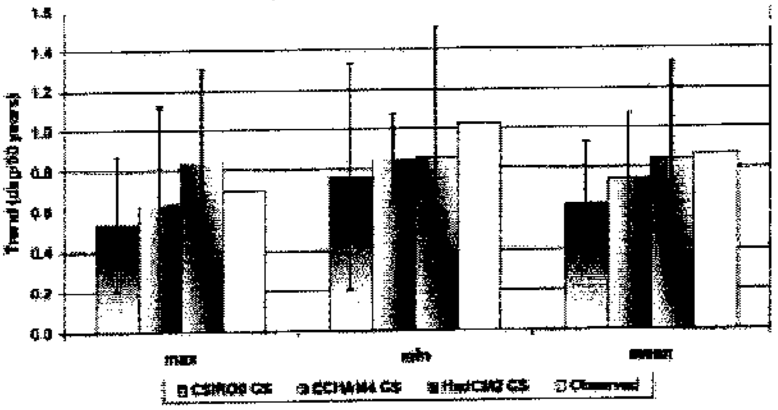


Figure 4:
Australian temperatures are now matching the global warming models



Observed trends in Australian average daily maximum (max), minimum (min), and mean temperatures over the period 1950-1999 compared with simulated trends from three different global climate models forced by observed increases in greenhouse gases and aerosols. The three climate models have been develop by CSIRO Australia, the Max Planck Institute for Meteorology in Germany, and the Hadley Centre in the UK. The error bar on each of the simulated warming trends is the uncertainty (90% confidence interval) in the 50-year trend associated with internal climate variability simulated by that model (Karoly 2001).

GLOBAL WARMING CONTRIBUTES TO AUSTRALIA'S WORST DROUGHT

GLOBAL WARMING INCREASES EVAPORATION RATES AND DRYING OF VEGETATION

A one-degree average temperature increase may appear to be a relatively small increase but it can have a major impact on the severity of drought.

Higher temperatures lead to higher evaporation of water from the soil, plants, lakes, and rivers. This places stress on water supplies and has a detrimental impact on agricultural productivity and vegetation health.

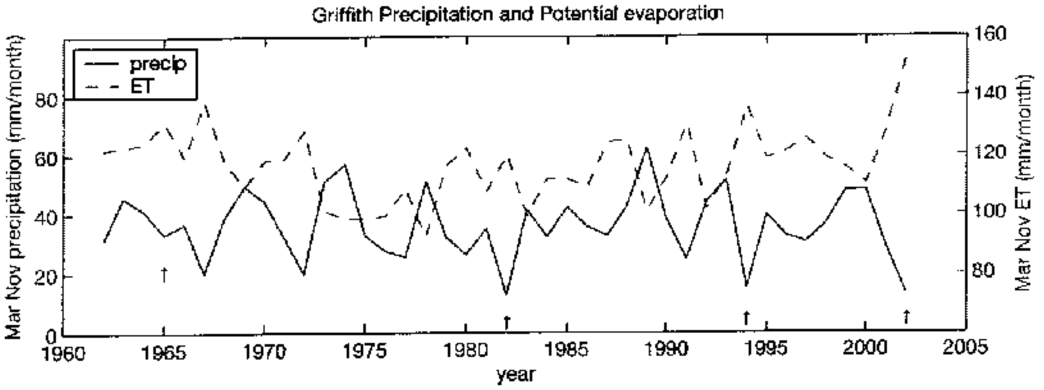
Under normal conditions evaporation rates in Australia are high, with almost 90 per cent of the precipitation that falls on the Australian continent returned through evapotranspiration to the atmosphere. As a result of the higher maximum temperatures, the evaporation rates in the Murray-Darling Basin in 2002 were significantly higher. Evaporation at Griffith, in the centre of the Murray-Darling Basin, in March-November 2002 was the highest on record and 10% higher than in other droughts, associated with the record high temperatures (Table 3, Figure 5).

Table 3:
Evaporation at Griffith in 2002 compared with other droughts

Year	Potential evaporation (mm/month)	Rainfall (mm/month)
2002	**152**	**13.3**
1994	136	15.0
1982	120	12.6
1965	131	33.1

Average potential evaporation and rainfall at Griffith in the Murray-Darling Basin for the 9 months March-November of major drought years since 1960. Potential evaporation is the evaporation expected from an open water surface, such as a reservoir. Data from CSIRO Land and Water, Griffith, available from 1960 only.

Figure 5.
Tracking evaporation in the Murray-Darling Basin



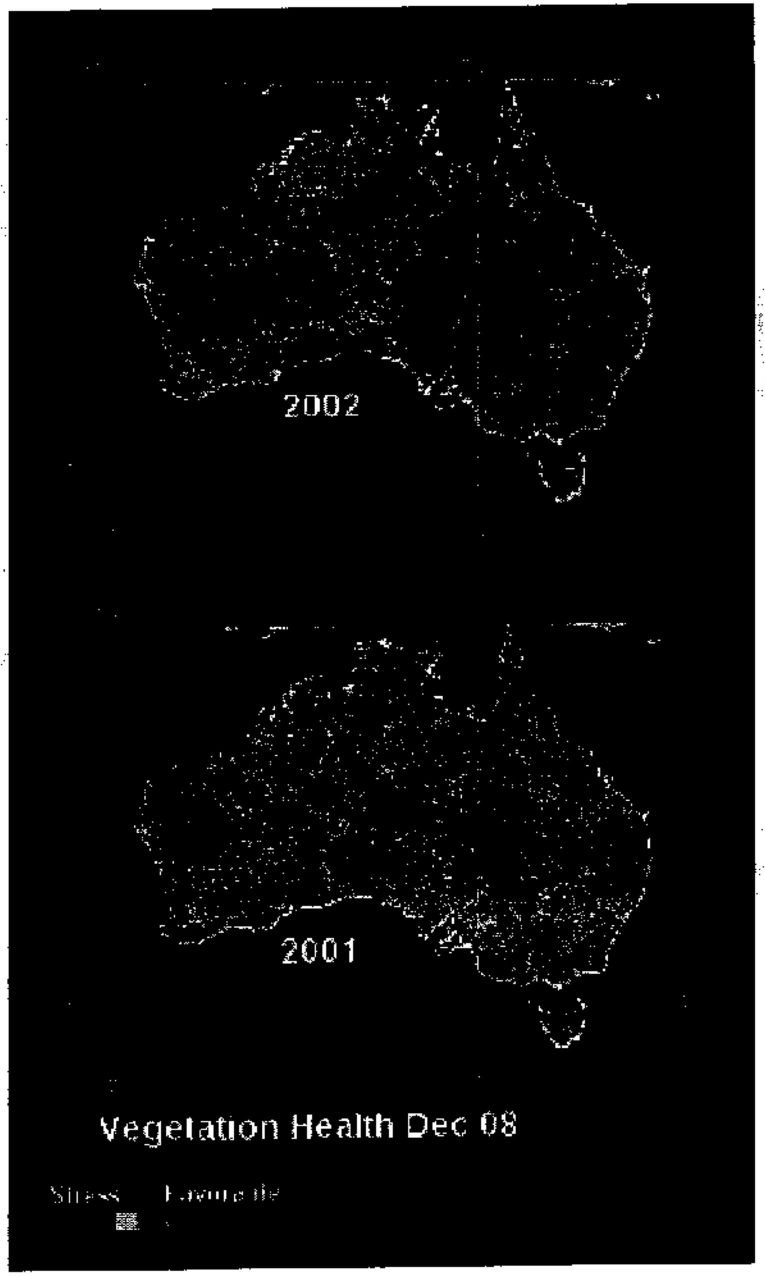
Interannual variations of March-November average monthly rainfall (solid blue line) and potential evaporation (dashed red line) for Griffith, in the Murray-Darling Basin. Small arrows indicate the 4 major drought years; 1965, 1982, 1994, and 2002, since 1960. Data from CSIRO Land and Water, Griffith.

GLOBAL WARMING CONTRIBUTES TO AUSTRALIA'S WORST DROUGHT

GLOBAL WARMING INCREASES EVAPORATION RATES AND DRYING OF VEGETATION

The higher temperatures have also placed Australian vegetation under severe stress, as captured by satellite data processed in the USA (Figure 6).

Figure 6. Vegetation stress in December 2002 compared with 2001



Vegetation health (condition) due to water availability and temperatures, based on satellite data. Drought regions with vegetation under stress are shown in red. (Kogan, 1997) Obtained from NOAA, USA from http://orbit35i.nesdis.noaa.gov/crad/sat/surf/vci/aus.html

GLOBAL WARMING CONTRIBUTES TO AUSTRALIA'S WORST DROUGHT

THE ECONOMIC IMPACT OF THE DROUGHT

Lower crop production due to the current drought will lead to lower export earnings for wheat, barley, cotton and canola in 2002 - 03 according to a recent forecast from the Australian Bureau of Agricultural Resource Economics (ABARE). Production of Australia's four major winter crops - wheat, barley, canola and lupins - is set to fall by 14.8 million tonnes in 2003.

Substantial reduction of irrigation water is also likely to result in major cuts in areas sown to irrigated summer crops such as rice and cotton in 2002-03. ABARE's Australian Crop Report estimates the area sown to cotton will be down 45 per cent from last season, while the rice area faces a slump of almost 70 per cent.

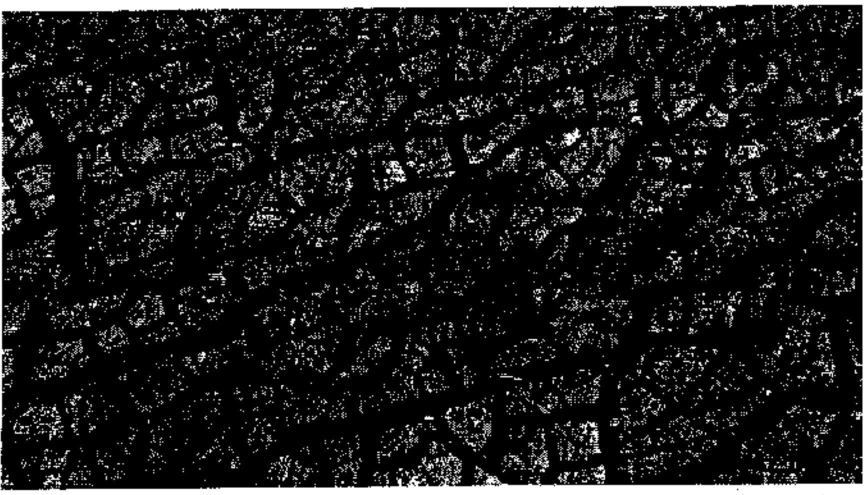
ABARE has forecast the area sown to summer crops will drop by 41 per cent in 2002-03, with grain production forecast to be down 59 per cent - this would make it Australia's smallest summer crop since the drought of 1982-83.

Australia's export earnings from crops are forecast to be down 19 per cent to $12.9 billion. ABARE has also forecast a drop of 3.7 per cent in the overall value of Australia's commodity exports due to the impact of the drought on agricultural performance.

The gross value of farm production is forecast to fall by 21 per cent to $30.4 billion in 2002-03 with earning from farm exports expected to drop by 13 per cent. The drought will reduce the rate of economic growth in Australia during 2002-03 by 0.75 per cent, reducing it to 3.1 per cent.

FUTURE DROUGHTS AND IMPLICATIONS FOR GOVERNMENTS

Global warming is a reality that is with us today. We can expect that the impact of drought in Australia will get worse as global warming accelerates. CSIRO (2001) has projected increases in Australian temperatures of between 1°C and 6°C by 2070, much greater than the increases over the last 50 years. These temperature increases would lead to even greater evaporation and water stress during future droughts, much worse than in 2002. CSIRO (2001) has projected up to a 45% decrease in stream flow in the Murray-Darling Basin by 2070. Climate models have projected a marked increase in the frequency of extreme droughts under global warming conditions (IPCC, 2001).



It is possible to slow global warming, keep temperature increases to the lower end of the scale and therefore reduce the severity of future droughts. Coordinated international action by governments is required to address the impacts of global warming. The Kyoto Protocol is the first international agreement with targets for reducing greenhouse gas emissions. It is the first step in slowing global warming. However, the Australian government has decided not to ratify the Kyoto Protocol. Mr Howard, the Australian Prime Minister, said in Parliament *"It is not in Australia's interest to ratify the Kyoto Protocol"* (Hansard, 5 June 2002). Any delay in greenhouse gas emission reductions will increase the likelihood of drought having worsening environmental and economic impacts, which is also not in Australia's interest.

REFERENCES

Abareconomics, Drought cuts commodity export earnings, 16 December 2002, www.abare.gov.au

Abareconomics, Drought to devastate summer crops too, 2 December 2002, www.abare.gov.au

CSIRO, 2001. *Climate change projections for Australia.* CSIRO Atmos. Res., 8 pp. Available from http://www.dar.csiro.au/publications/projections2001.pdf

IPCC, 2001. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., eds. Cambridge Univ. Press, Cambridge, 881 pp.

Jones, D. A., and Trewin, B. C., 2000. On the relationships between the El Niño – Southern Oscillation and Australian land surface temperature. *Int. J. Climatol.*, **20**:697-719.

Karoly, D., 2001. Interannual and longer-term variations of Australian mean climate parameters from observations and model simulations. *Understanding the climate of Australia and the Indo-Pacific region: 13th Annual BMRC Modelling Workshop,* BMRC Research Report No. 84, 49-52, Bureau of Meteorology, Australia.

Kogan, F. N., 1997. Global drought watch from space. *Bull. Amer. Meteor. Soc.*, **78**:621-636.

Nicholls, N., 1985. Towards the prediction of major Australian droughts. *Aust. Met. Mag.*, **33**:161-66.

Williams, A. A. J., D. J. Karoly and N. Tapper, 2001. The sensitivity of Australian fire danger to climate change. *Climatic Change*, **49**:171-191

CONTACT DETAILS

Copies of this paper can be downloaded from WWF Australia's website – www.wwf.org.au

Professor David Karoly, School of Meteorology, University of Oklahoma, Norman, OK, USA. Previously at Monash University.
Till 18 Jan: ph. (03) 9803 4565.
From 20 Jan: (In USA) ph. +1-405-325 6561, fax. +1-405-325-7689,
email: dkaroly@.rossby.metr.ou.edu

Dr James Risbey, Centre for Dynamical Meteorology and Oceanography, School of Mathematical Sciences, Monash University, Clayton VIC 3800
Ph: (03) 9905 4461, Fax: (03) 9905 5020,
email: james.risbey@sci.monash.edu.au

Anna Reynolds, Climate Change Specialist, WWF Australia, Sydney.
Phone: (02) 8202 1204 Mobile: 0419 547 217
email: areynolds@wwf.org.au

For a full list of WWF Australia publications on a wide range of conservation issues, please contact us on publications@wwf.org.au or call (02) 9281 5515

First published in 2003 by WWF Australia.

Head Office
WWF Australia, GPO Box 528, Sydney, NSW, Australia Tel: +612-9281-5515 Fax: +612-9281-1060
www.wwf.org.au enquiries@wwf.org.au

WWF is one of the world's largest and most experienced independent conservation organizations, with almost 5 million supporters and a global network active in more than 90 countries.

WWF Australia's mission is to conserve biodiversity in Australia and the Oceania Region. We have 180 active projects focusing on 5 priority areas that address current conservation challenges.

For in-depth information on all our work, go on-line at www.wwf.org.au or call our toll free number 1800 032 551.

THE SENSITIVITY OF AUSTRALIAN FIRE DANGER TO CLIMATE CHANGE

ALLYSON A. J. WILLIAMS [1,*], DAVID J. KAROLY [2] and NIGEL TAPPER [1]

[1] *Department of Geography and Environmental Science, Monash University, Clayton, Victoria, Australia 3168*

[2] *CRC Southern Hemisphere Meteorology, Monash University, Clayton, Victoria, Australia 3168*

Abstract. Global climate change, such as that due to the proposed enhanced greenhouse effect, is likely to have a significant effect on biosphere-atmosphere interactions, including bushfire regimes. This study quantifies the possible impact of climate change on fire regimes by estimating changes in fire weather and the McArthur Forest Fire Danger Index (FDI), an index that is used throughout Australia to estimate fire danger. The CSIRO 9-level general circulation model (CSIRO9 GCM) is used to simulate daily and seasonal fire danger for the present Australian climate and for a doubled-CO_2 climate. The impact assessment includes validation of the GCMs daily control simulation and the derivation of 'correction factors' which improve the accuracy of the fire danger simulation. In summary, the general impact of doubled-CO_2 is to increase fire danger at all sites by increasing the number of days of very high and extreme fire danger. Seasonal fire danger responds most to the large CO_2-induced changes in maximum temperature.

1. Introduction

This assessment of potential changes in the Australian fire-climate system due to a doubling of the concentration of atmospheric CO_2 includes validation of the control simulation, simulation of potential climate change, *quantitative* analysis of impacts on the fire-climate system, and comparison with the impact of existing climate variability on the system. Previous climate change impact studies suggest increases in fire danger over much of Australia (Beer and Williams, 1995), but there has been little quantification of impacts, particularly with respect to historical variability. Other assessments of the impact of climate change on fires are often merely inferences derived from the suggested increase in occurrence of drought due to global warming. The inference is that increased drought will also cause an increase in fire occurrence, but GCM impact studies and empirical fire histories suggest that this is not always the case (e.g., Bergeron and Flannigan, 1995; Takle et al., 1994). The large spatial variability of climate change and of fire environment types precludes any such generalisations of an overall increase in fire with global warming.

---

[*] Current address: Queensland Centre for Climate Applications, Department of Primary Industries, Toowoomba, Queensland, Australia 4350.

Climatic Change **49:** 171–191, 2001.

The sensitivity of fire and fire danger to global warming has been assessed for other regions, mainly in the Northern Hemisphere. Potential impacts include increases in the area of extreme fire danger in Russia and Canada (Stocks et al., 1998; Fosberg et al., 1996) and general increases in fire danger (Flannigan and Van Wagner, 1991). Changes in lightning frequency across the Northern Hemisphere are also significant (Price and Rind, 1994).

Kirschbaum and Fischlin (1996) and Allen-Diaz (1996) comment in the Intergovernmental Panel on Climate Change Scientific Assessment of Climate Change (IPCC, 1996) that in Australian ecosystems changes in fire frequencies are likely to have major impacts on the composition, age-distribution and biomass of forests and rangelands. However, there are no quantitative details of these expected changes in fire frequency, and analysis does not extend past inferences of potential future fire behaviour in 2 × CO_2 conditions based on fire-system behaviour during past episodes of drought. There is also a supposition that because of effective control measures, large-scale fires will be rare in the temperate zone and will be limited to drier regions of Australia (Kirschbaum and Fischlin, 1996). This is a contentious argument (a similar argument about the effectiveness of control measures is presented by Trabaud et al. (1993) given that in the past, extreme fires have coincided with extreme weather conditions and large conflagrations have occurred during the last 40 years in temperate, managed forest regions such as in Tasmania, Victoria, and NSW.

The following discussion presents the data and models used for the study, a validation of the climate model, the doubled-CO_2 fire danger scenarios and their context with respect to historical extremes, and a discussion followed by conclusions.

2. Data and Models

2.1. FIRE MODEL

A fire regime can be defined by fire intensity, fire frequency, and the season of burn. There are various indices, used mainly for predictive purposes, that represent these fire regime components. In south-eastern Australia, the McArthur Forest Fire Danger Index Mark 5 (FDI, McArthur, 1967) is a fire weather based index commonly used to represent the daily fire danger. The FDI was derived from approximately 400 experimental forest fires, conducted in a variety of fuels in low to medium quality dry sclerophyll forests with a fuel loading of 12 t/ha, in south-eastern Australia. Fire danger is indicative of the chances of a fire starting, its rate of spread, intensity and difficulty of suppression. As well as its regionally-specific applications (which is the use for which it was intended), the FDI is also a valid indicator of forest fire danger over the entire continent used for comparison of intra-seasonal and inter-annual fire danger variability. The FDI is defined as:

$$\mathrm{FDI} = 1.275D^{0.987} * [\exp(0.0338T - 0.0345H)] * [\exp(0.0234V)],$$

where T = air temperature °C, V = wind speed km/hr in the open at 10 m height, H = relative humidity %,

$$D \text{ is a drought factor} = [0.191(I + 104)(N + 1)^{1.5}]/[3.52(N + 1)^{1.5} + R - 1)],$$

where I = Keetch Byram Drought Index (Keetch and Byram, 1968), R = precipitation, N = days since rain. (Equations from Noble et al. (1980)).

On a seasonal scale the FDI is most sensitive to seasonal relative humidity, except at the two northern sites (see Figure 1) where wind speed is more influential on FDI interannual variability.

Although fire regime characteristics are highly coupled with weather and climate, the relationships are often complex. Variations in fuels also influence the properties of a fire regime such as fire frequency and fire intensity. However, under extreme conditions, the influence of the variation of fuels or structure within a vegetation community (mainly on fire frequency rather than intensity) may frequently be overridden by large-scale topographic features and weather patterns (examples from ecosystems outside Australia include Bessie and Johnson (1995) and Swetnam (1993)).

2.2. CLIMATE MODEL

The CSIRO 9-level general circulation model (CSIRO9, Watterson et al., 1995) is a global atmosphere, slab-ocean climate model. It simulates two scenarios that are used to assess the impact of doubling atmospheric CO_2 on fire danger: a 30-year $1 \times CO_2$ simulation and a 30-year doubled atmospheric CO_2 simulation. The $1 \times CO_2$ simulation is the radiation forcing for a CO_2 concentration of 330 ppm (around the year 1975) without other trace gas or aerosol effects (Watterson et al., 1995). Continental climate projections have already been developed for Australia for annual and seasonal time frames (for example, Whetton et al., 1996), but a study of the fire-climate system requires more specific analysis than has been done previously. CSIRO9 has 43 grid points covering the Australian landmass with grid-box dimensions of 400 km by 650 km. At each grid point, the model simulation of the daily data required for the four FDI input parameters and the FDI itself are analysed. The daily data are mean relative humidity, mean wind speed, maximum temperature, and precipitation. The mean relative humidity and mean wind speed variables are slightly different from the observed variables of minimum relative humidity and maximum wind speed mentioned in Section 2.3. Section 2.4 addresses these differences as well as the quality of the GCM's simulation of maximum temperature and precipitation.

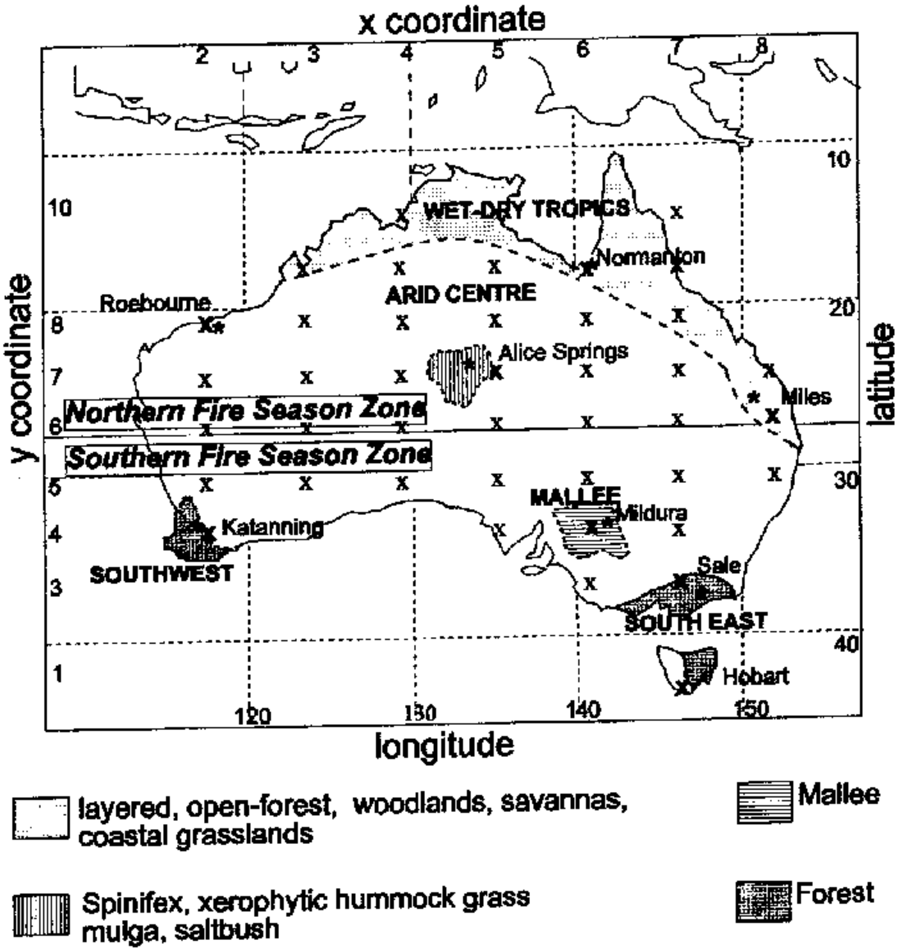


Figure 1. The location of CSIRO9 grid points (×), the grid points selected for model validation (in bold), and the meteorological observing stations used in the study (∗). The boundary between the northern and southern fire season zone is marked, as are the five biogeographical regions represented by the selected grid points and observing stations. The primary vegetation type of the five regions is also shown.

2.3. METHOD

Figure 1 shows the distribution of grid points and the division of the continent and the grid points into two primary fire season zones: the northern zone (fire season from July to November) and the southern zone (fire season from November to March). The sum of the daily FDI for the entire fire season is called the seasonal cumulative FDI (seasonal ΣFDI). For the two fire season zones, the spatial distribution of seasonal ΣFDI and fire weather from CSIRO9 control simulations are compared with 2 × CO_2 simulations, and the statistical significance of any changes noted.

In addition to identifying continental-scale changes in seasonal fire danger, four grid points in each of the two fire season zones (that is, a total of eight sites) have been selected for more detailed examination to indicate the significance of changes in the frequency distributions of daily fire weather and FDI. Student's t-test and the Chi-squared test are used to test for statistical significance. These eight grid points are representative of five distinct climate-biogeographical regions (see Figure 1). Each grid point is assumed to be representative of a large area, which is reasonable given that climate variations usually involve large spatial scales.

To provide a historical context of changes in extreme fire danger conditions, the daily and seasonal fire danger and fire weather for a 33-year period (1960–1992) are also calculated. Archived data from each station were obtained from the National Climate Centre at the Australian Bureau of Meteorology. The meteorological data obtained were daily rainfall, daily maximum temperature, three hourly wind speed and three hourly dew point temperatures from 1960 to 1992. Daily minimum relative humidity is calculated from the temperature and dew point temperature at the time when the maximum temperature was recorded. Recently, Williams and Karoly (1999) have used this data to examine the impact of the El Niño-Southern Oscillation on fire weather and fire danger throughout Australia. They have shown coherent patterns of increased fire danger in south-eastern and central Australia during El Niño episodes.

These data are also used to validate the control simulation of CSIRO9. Ideally, the control simulation should be validated against observed area-average data computed from multiple sites within each grid-box (Mearns et al., 1990). However, while daily temperature and rainfall data are available for many observing stations within each grid-box, daily humidity and wind data are more difficult to obtain. Therefore since it was not possible to obtain sufficient data for such a model validation, single observing stations had to be used (the names of which are shown in Figure 1). This validation test is therefore limited since observations at a point are being compared with an area-average simulation.

2.4. MODEL VALIDATION

The CSIRO9 control simulation of the FDI is validated by comparing it with the observed FDI at each of the eight sites/grid points. As well as comparing the mean values of the observed and modelled data sets, the frequency distributions of daily occurrences of the two data sets are also compared. We use a significance level of 0.05 for the statistical tests. As indicated by the chi-square values in Table I, the 1 × CO_2 fire season simulation of the daily FDI is not suitably accurate nor are the simulations of the four FDI input parameters. At grid points (7,3)/Sale, (2,4)/Katanning and (2,8)/Roebourne, the FDI as simulated by CSIRO9 is higher than observed, and at the other five grid points the FDI is too low. The differences between the modelled and observed fire danger statistics are anticipated for three reasons. Firstly, as mentioned previously, single point stations of observed data are compared with the area-averaged simulations of the model. Secondly, the horizontal and vertical resolutions are coarse and physical parameterisations in the model are simplifications of sub-grid-scale processes. Lastly, CSIRO9 produces daily mean relative humidity rather than daily minimum relative humidity and daily mean wind speed at 970 hPa rather than the maximum wind speed used to calculate the FDI from the observed data. In Beer and Williams (1995), the inadequacies of the CSIRO9 humidity and wind simulations were overcome by physically-derived manipulation of the data at grid point (7,3), the Sale site. However, background research for this study shows that when considering all eight validation grid points, such a method of correcting the data does not provide the same degree of improvement as do purely statistically derived modifications (that is, by modifying the mean and standard deviation).

For both groups of four grid points in the two fire season zones, the daily distributions of the GCM control FDI are compared with the observed FDI. The four modelled fire weather parameters are manipulated in order to achieve the best modelled average FDI distribution over all four grid points (as measured by chi-square values). In order for the modelled data to simulate the observed data, the modelled mean and standard deviation need to approximate the observed mean and standard deviation. This is achieved by applying a linear scaling to each daily data value, $X = a * Y - b$, where X is the observed data value, Y is the modelled data value, and a and b are the correction factors.

At the four sites in the southern fire season zone, the model FDI is most sensitive to corrections made to relative humidity. Corrections made to temperature and rainfall are also important and significantly impact on the FDI. The distribution of wind speed was so highly variable that a correction factor could not be found. The resultant model control FDI for the Southern Fire Zone is therefore calculated by modifying relative humidity, rainfall and temperature using the formulae listed in Table I. Examples of the change in FDI distribution before and after modification are shown in Figure 2. As in the Northern Fire Zone, the same scaling formulae were used at all sites. In contrast, the CSIRO9 simulation of the FDI in the Northern Fire Zone is improved by adjusting only the rainfall parameter. The frequency distributions of the other three FDI parameters were not suitably responsive to corrections. Despite the common scaling factors at each site, there are still significant differences between the model and observed distributions in some cases. The following discussion of doubled-CO_2 fire danger scenarios is based on an FDI calculated with the corrected FDI parameters.

TABLE I

For each of the eight validation grid points and nearest meteorological stations, χ^2 values are listed for the comparisons of (i) the observed and CSIRO9 daily fire weather and FDI and (ii) the modified CSIRO9 and observed data. The formulae used for the modification are listed. The fire weather variables are abbreviated as: max temp is maximum temperature, min Rh is minimum relative humidity, and max WS is maximum wind speed. Differences are significant ($p > 0.10$) at χ^2 values of 18.5

Northern grid-points					Southern grid-points				
Daily variables	2,8 χ^2 Roebourne	6,9 χ^2 Normanton	5,7 χ^2 Springs	8,6 χ^2 Miles	Daily variables	2,4 χ^2 Katanning	6,4 χ^2 Mildura	7,1 χ^2 Hobart	7,3 χ^2 Sale
FDI					FDI				
Control vs. observed	42.4	48.1	58.6	72.2	Control vs. observed	45.8	20.7	24.6	24.8
Modified vs. observed (using only rainfall correction)	43.8	2.3	17.5	5.8	Modified vs. observed (using all corrections)	28.8	23.2	3.0	22.4
Max. temp.					Max. temp.				
Control vs. observed	7.8	24.0	11.8	59.3	Control vs. observed	22.9	20.2	27.6	39.8
Modified vs. observed	30.5	22.7	4.8	40.6	Modified vs. observed	7.5	16.0	78.1	16.2
$0.95 * \text{model}$					$1.2 * \text{model} - 6$				
Min Rh					Min Rh				
Control vs. observed	61.2	16.4	74.4	23.3	Control vs. observed	20.4	55.7	17.5	39.6
Modified vs. observed	61.4	15.2	63.5	17.8	Modified vs. observed	31.5	35.5	34.2	17.3
$0.95 * \text{model}$					$1.3 * \text{model} - 10$				
Rainfall					Rainfall				
Control vs. observed	5.2	93.9	63.8	87.2	Control vs. observed	6.1	21.9	103.4	14.1
Modified vs. observed	3.9	14.2	6.1	4.4	Modified vs. observed	24.4	3.4	2.9	30.6
$1.3 * \text{model} - 5.1$					$1.3 * \text{model} - 5.1$				
Max WS					Max WS				
Control vs. observed	27.7	28.1	32.6	63.3	Control vs. observed	71.0	13.9	71.6	7.3
No modification factor					$0.7 * \text{model}$	37.6	19.8	34.0	13.9

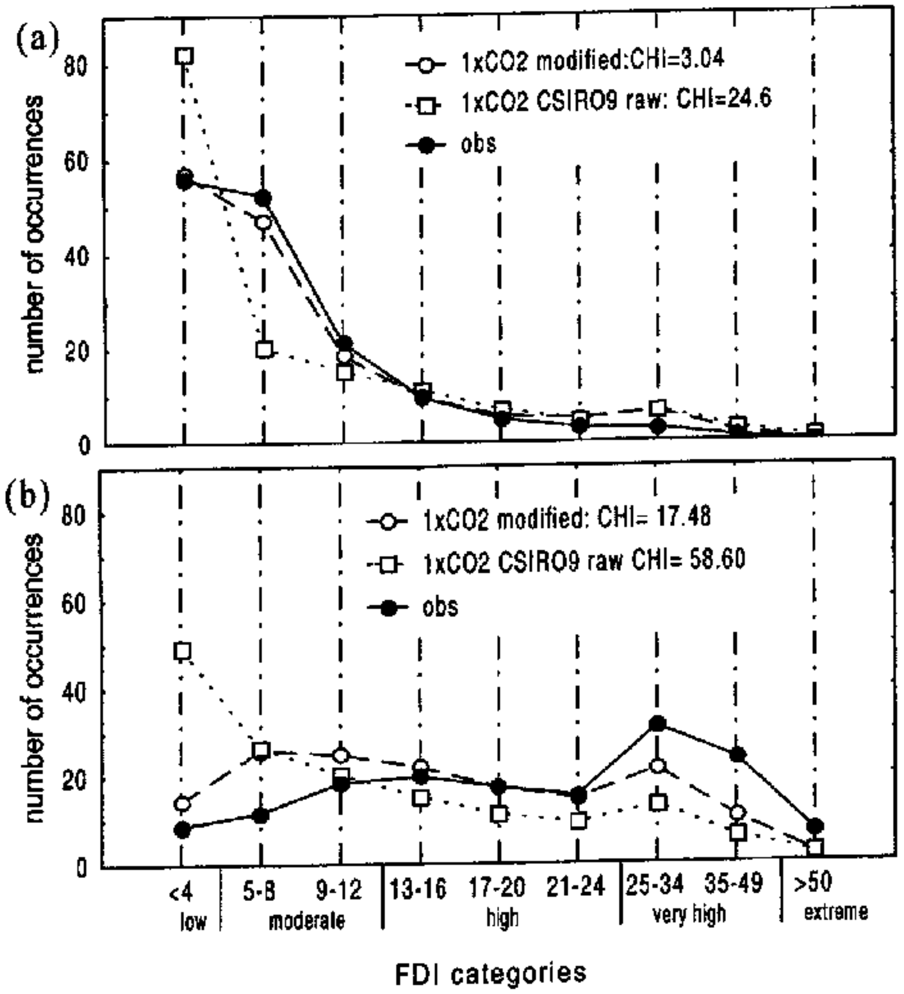


Figure 2. The CSIRO9 unmodified and modified control (1 × CO_2) simulations of the daily frequency distribution of the FDI, and the frequency distribution of the observed FDI of (a) grid point (7,1)/Hobart in the Southern Fire Zone, and (b) grid point (5,7)/Alice Springs in the Northern Fire Zone. The χ^2 values indicate the degree of difference between (i) the modified CSIRO9 simulation and the observed data, and (ii) the unmodified simulation and the observed data (also listed in Table I). The FDI values are categorised according to the classification of McArthur (1967).

3. Doubled CO_2 Fire Danger Scenarios

The impact of doubling atmospheric CO_2 on the fire regimes in a region is determined by considering the influence on the following aspects of fire danger: changes in the spatial distribution of seasonal ΣFDI; changes in frequency distribution of daily FDI; and changes in the seasonality of fire danger. The environmental impact of many of these changes is dependent on the existing levels of variability. Therefore, changes due to doubled CO_2 are placed into perspective by considering the variability of historical fire danger. Firstly though, the changes in fire weather are examined and also the sensitivity of fire danger to changes in each fire weather parameter.

3.1. THE SENSITIVITY OF SEASONAL ΣFDI TO CHANGES OF FIRE WEATHER

The response of FDI to a doubling of atmospheric CO_2 depends on the impact on fire weather. The modelled impact of 2 × CO_2 on each fire weather variable is different at different locations, and therefore the FDI will also have a disparate response to the changes in each variable.

Doubling CO_2 has a significant impact on the seasonal averages of all the fire danger parameters except wind speed. As shown in Figure 3a–d the general direction of change is: maximum temperature increases, minimum relative humidity decreases, and rainfall increases in the southern zone. The change in the probability distributions of daily values of each parameter at each of the eight sites does not have the same high degree of statistical significance. As with the mean seasonal averages, daily maximum temperatures have significant increases. Daily minimum relative humidity changes are only significant at Alice Springs and Miles, and rainfall and wind speed have no significance in their changes. In must be noted that, in most GCMs, rainfall is the most poorly modelled of the four fire weather parameters.

Figure 4 depicts the response of seasonal ΣFDI to changes in the individual FDI parameters (that is, all parameters are held constant at their 1 × CO_2 value, except the parameter of interest). Sites in the northern and southern fire zones are very similar in their responses. Changes in seasonal ΣFDI are most sensitive to changes in maximum temperature. Within each of the two zones the sensitivity to the other three fire weather variables is different depending on location, although changes in wind speed tend to have the least impact.

3.2. CHANGES IN THE SPATIAL DISTRIBUTION OF SEASONAL CUMULATIVE FDI

The control simulation indicates that there is greater fire danger in the western area of the northern fire season zone than in the east. As shown in Figure 5, in the 2 × CO_2 simulation the fire danger increases significantly over the entire northern

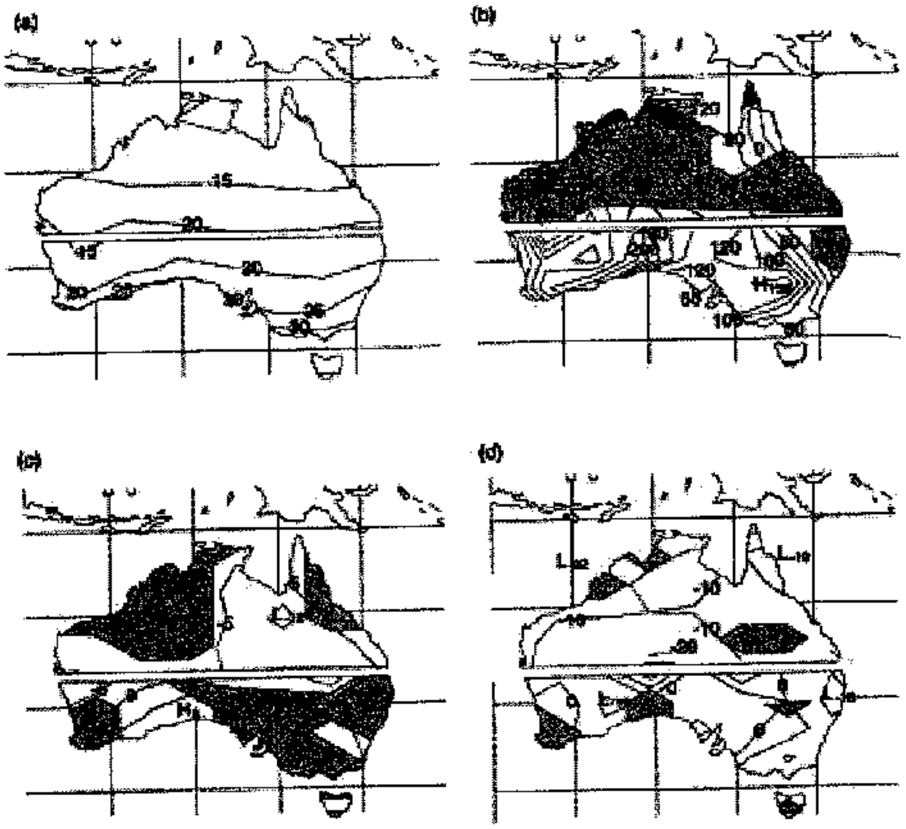


Figure 3. The impact of doubling CO_2 on simulated seasonal fire danger parameters in the northern and southern fire season zones (as delineated by the dividing 'split' in the maps). The percentage change in the value of the parameter from the 1 × CO_2 scenario to the 2 × CO_2 scenario is shown for (a) maximum temperature, (b) rainfall, (c) wind speed, and (d) relative humidity. A decrease in value is indicated by a negative value. All changes are statistically significant (10% level) except where shaded.

zone. The largest increases (30%) occur on the north east coast and in the southernmost reaches. The smallest impact is in western Queensland: this grid-point (6,8) is also one of extremely high rainfall in the model (a poor simulation of reality) which dominates the FDI.

The Southern zone control scenario shows that the west coast of the continent has greater seasonal ΣFDI than the east coast, with the greatest fire danger occurring in the south-east of Western Australia. The impact of doubling CO_2 is to increase the FDI throughout the entire southern zone, with the greatest changes (increases of 40%) occurring in northern NSW and south-east Western Australia. However, the main gradient of change is in a north-south direction and has little

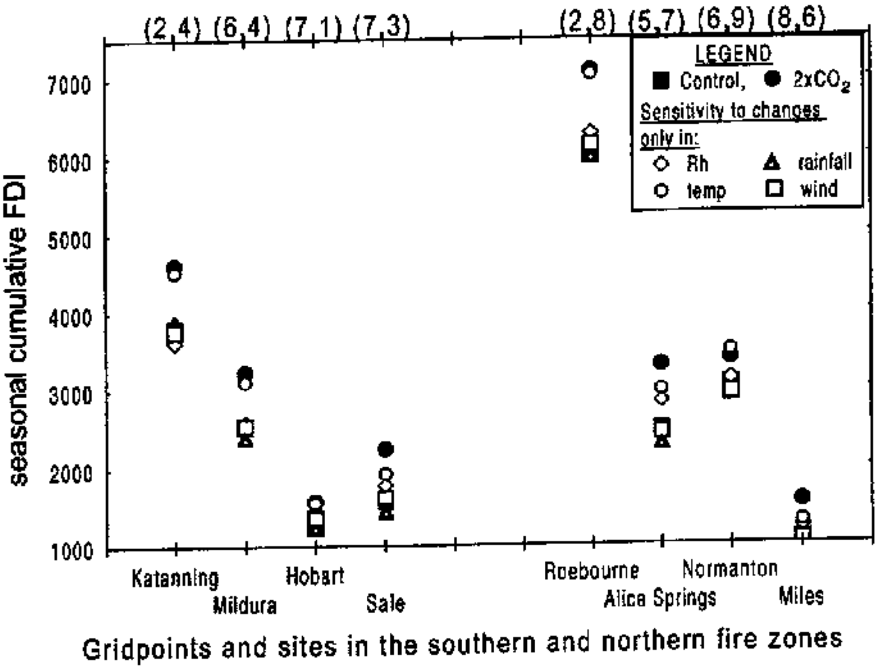


Figure 4. The control and 2 × CO_2 seasonal ΣFDI, and its sensitivity to 2 × CO_2-induced changes in each fire weather parameter. Clearly, all sites are most sensitive to the 2 × CO_2 changes in temperature.

impact on the overall pattern of the FDI spatial distribution. As shown in Figure 5, most of the changes are statistically significant.

The impact of doubled CO_2 on seasonal fire danger is greater on the southern fire season than on the northern. Within these two zones the resultant change increases moving southward.

3.3. CHANGES IN THE FREQUENCY DISTRIBUTION OF DAILY FDI

This section tests the hypothesis that there is a statistically significant change in the daily FDI distribution in a 2 × CO_2 climate scenario compared with the distribution of the control simulation. As shown in Figure 6, at each of the eight grid-points/sites representative of the two fire zones the control FDI distributions vary widely between stations. The accuracy of the simulations also varies (see Table I). Given this range of distributions, it is not unexpected that the 2 × CO_2 FDI distributions also vary widely (also shown in Figure 6).

In the Northern fire season zone, the mean daily FDI increases at all sites, and the frequency of high FDI occurrences increases markedly. The grid-point with the greatest change in daily FDI is Miles on the east coast. Only at Miles (χ^2 =

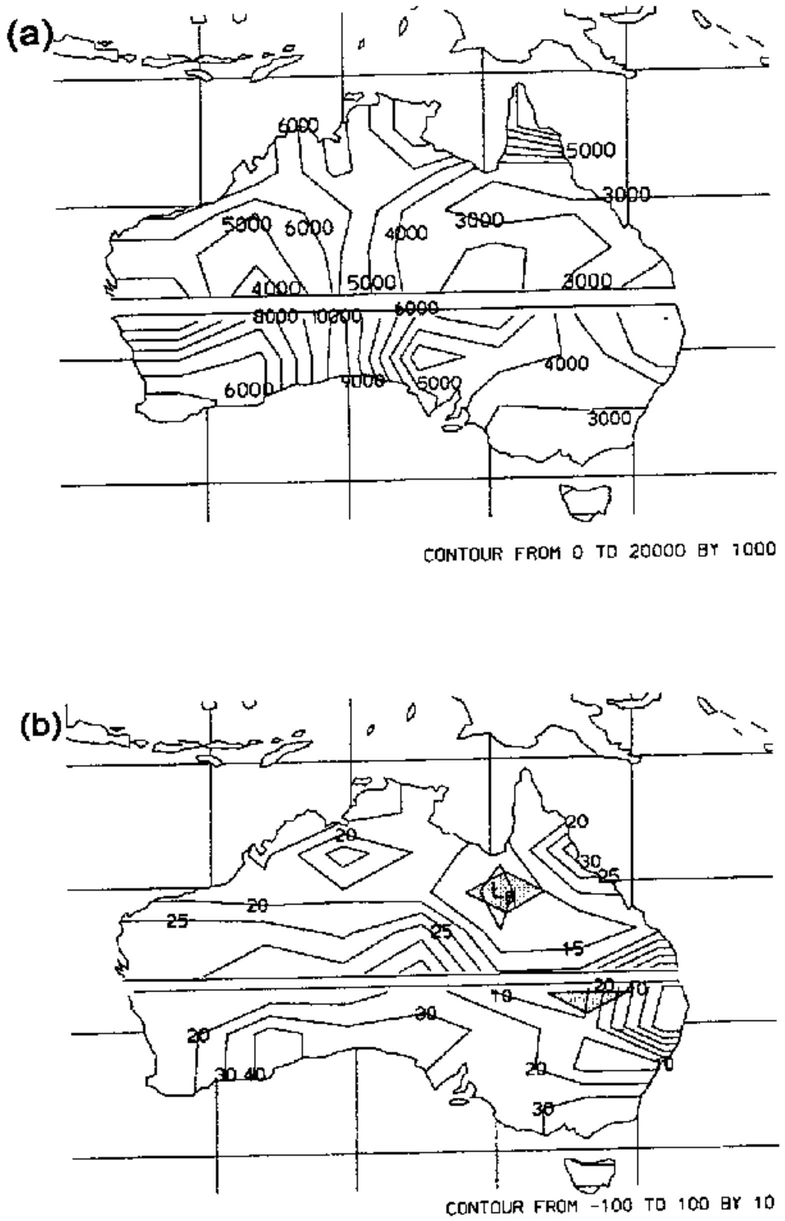


Figure 5. The spatial distribution of (a) the mean seasonal ΣFDI in the northern and southern fire zones for the CSIRO9 2 × CO_2 fire weather scenario, and (b) the percentage difference between the 2 × CO_2 and 1 × CO_2 values. Shaded areas are not statistically significant at the 10% level.

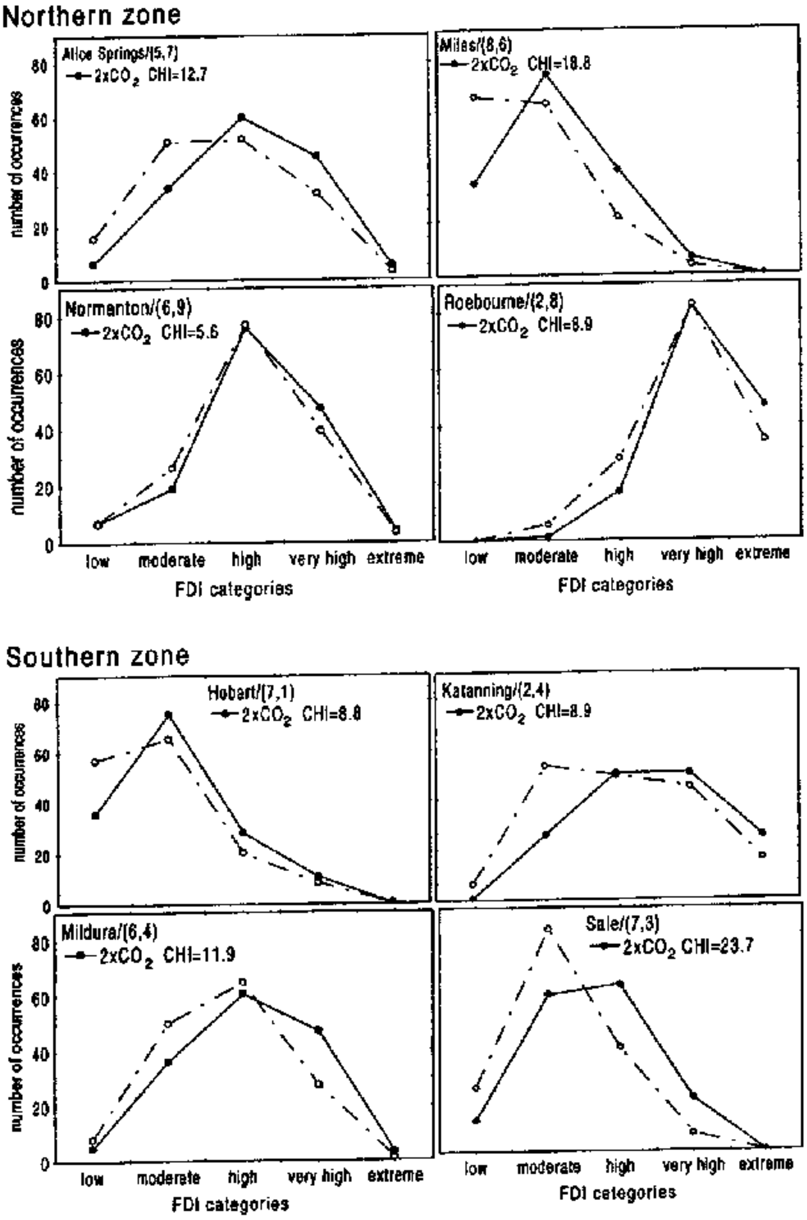


Figure 6. The frequency distributions of daily FDI of the control (dashed line) and 2 × CO_2 (solid line) simulation. Chi-square values indicating the difference between the 2 × CO_2 and 1 × CO_2 simulations are listed at the top of each plot. The critical value of χ^2 at the 10% level is 12.02. The two distributions are significantly different at Alice Springs, Miles, Sale, and Mildura is border-line.

18.8) and Alice Springs ($\chi^2 = 12.7$) are there significant changes between the control and 2 × CO_2 distributions. At all sites in the Southern zone, a doubling of CO_2 causes a decrease in the number of low FDI occurrences and an increase in the occurrence of high FDIs. However, only at Sale is the change statistically significant.

3.4. IMPACT ON FIRE DANGER SEASONALITY

All months at all sites have higher FDI in 2 × CO_2 conditions than 1 × CO_2. However, the *relative* magnitude of each month's FDI also changes. Of the four sites that were allocated a northern fire season zone (categorisation based on observed FDI) only Roebourne has a fire season comprised of the same months in both the 1 × CO_2 and 2 × CO_2 scenarios (i.e., it has no response to 2 × CO_2). Miles has a shorter fire season in the 2 × CO_2 scenario, and Normanton and Alice Springs (shown in Figure 7) have longer fire seasons. At Normanton and Miles the greatest FDI severity occurs earlier in the season. Of the four southern fire season sites, the length of the fire season remains the same at Hobart and Katanning. Mildura (Figure 7) has shorter season, with the month of greatest intensity occurring later, and Sale has a longer season.

4. Comparing 2 × CO_2-Induced Changes with Levels of Observed Variability

It has been shown that for some regions CSIRO9 projects a significantly different fire danger regime for doubled CO_2 conditions than for control conditions. As well as the absolute changes in the fire danger, it is the changes relative to existing levels of variability that often determine the actual impact of higher fire danger. That is, have these levels of fire danger already been experienced? Do the modelled changes fall within the levels of observed variability?

The impact of doubling CO_2 is put in perspective in Figure 8 which has been compiled utilising extreme data from the observed data set, and the control and doubled CO_2 simulation data. The impact of doubling CO_2 is analysed by comparing the difference between the mean of the control and 2 × CO_2 seasonal ΣFDI, with the difference between composites of high and low observed seasonal fire danger during 1960–1992. The mean values of the six highest seasonal ΣFDI years and those of the lowest six seasonal ΣFDI years within this time period are presented alongside the 33-year observed mean so a complete picture is presented of the range of seasonal ΣFDI experienced in this period. At most sites Williams and Karoly (1999) have shown that the high FDI seasons are associated with El Niño episodes. The low and high FDI composites are composite differences between El Niño and La Niña events for most sites. Hence, the difference between the composites indicates the range of natural variability between current large-scale climate variations.

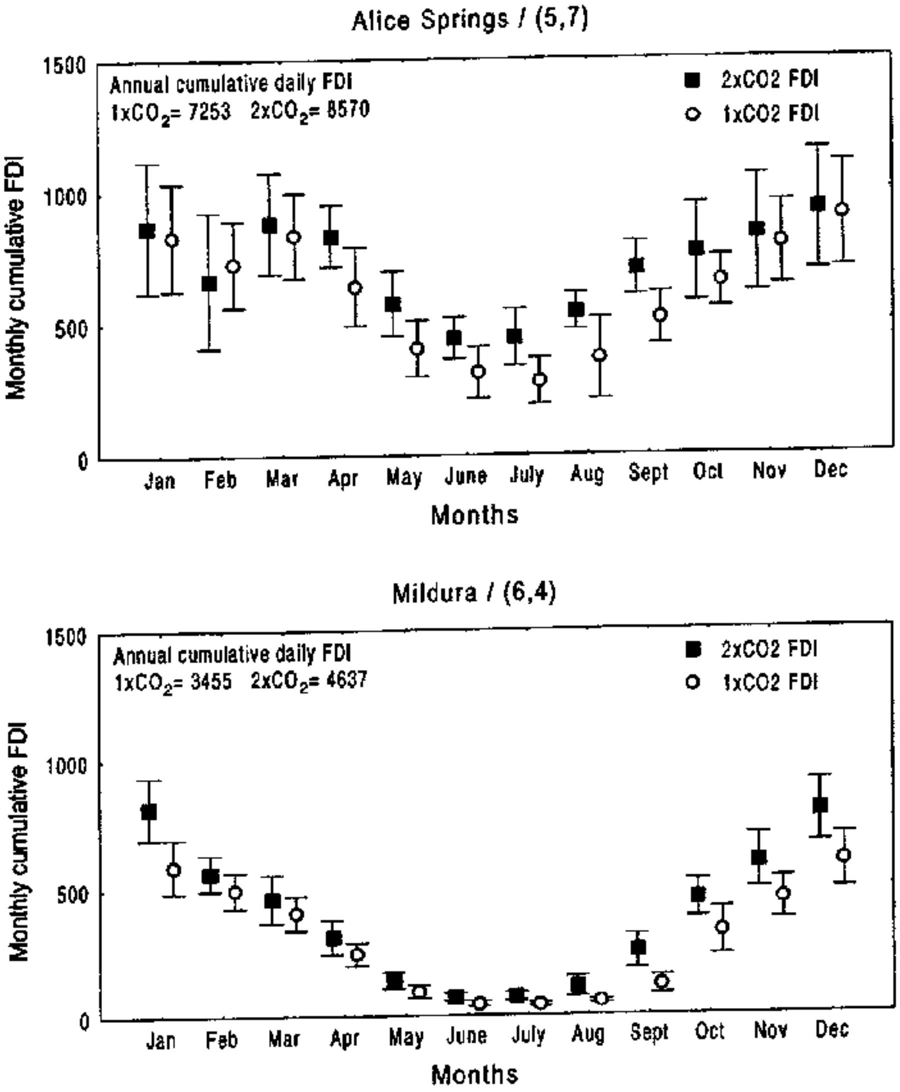


Figure 7. Examples of the doubled CO_2-induced changes in the seasonality of fire danger.

It has already been ascertained that the change in mean seasonal ΣFDI between $1 \times CO_2$ and $2 \times CO_2$ conditions is statistically significant at all sites. However, these changes are not as large as the existing variability. For example, at Hobart the difference between the $1 \times CO_2$ mean and the $2 \times CO_2$ mean is 297 FDI units, but the difference between the extreme composites in the observed data is 775 FDI units. This observation is magnified in the northern zone where, at least at the four

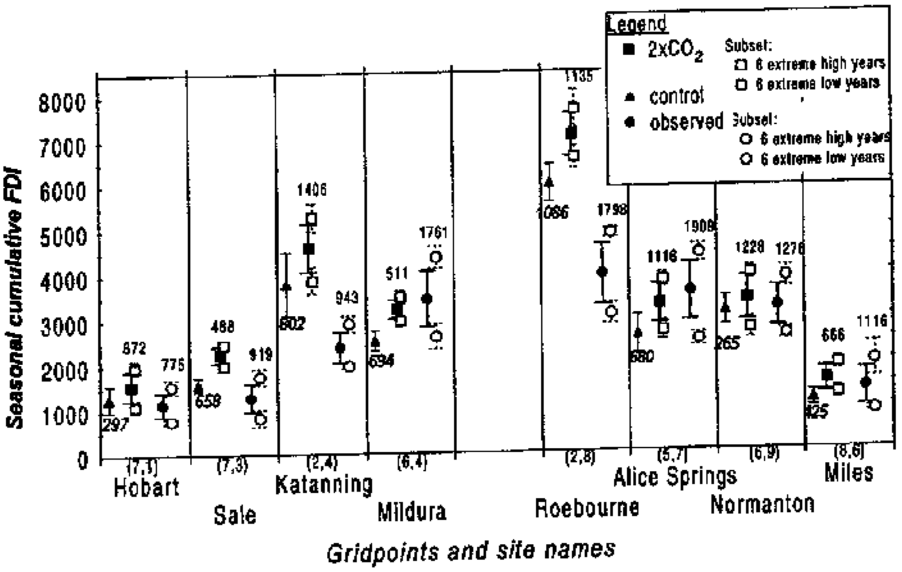


Figure 8. Thirty year means and standard deviations (solid whiskers) of control and 2 × CO_2 simulated seasonal ΣFDI (triangles and squares), and observed seasonal ΣFDI (circles). A wider range is also given for 2 × CO_2 (open squares and dashed whiskers) and observed (open circles and dashed whiskers) data sets by plotting two composites of 6 year extreme high and low seasonal ΣFDI occurrences. Each bold italic number is the difference between the means of 2 × CO_2 and control simulations (for example, 279 is Hobart (2 × CO_2 mean – observed mean)) and the plain numbers are the difference between the means of the high composite and the low composite (for example, 872 is Hobart (2 × CO_2 high – 2 × CO_2 low).

selected sites, the differences between the observed extremes are greater than in the south (except for Mildura which has relatively large variability compared with the other 3 southern stations). Therefore, the inference is that the change in mean conditions from control to a doubled CO_2 atmosphere is less than the existing range of extreme fire seasons.

Looking more closely at the 2 × CO_2 simulation and comparing the range between the extreme composites with the extreme composites at the corresponding observing station, there are clear changes. It is only at Hobart and Katanning that there is a greater range of extreme seasons in the 2 × CO_2 scenario than in the observed data set. The change from control to 2 × CO_2 fire severity is less than existing extremes at all other six stations, and the range of 2 × CO_2 extreme composites are less than present.

5. Discussion

The results presented so far indicate that the CSIRO9 projection of the impact of doubling CO_2 on fire danger is a significant effect, the strength of which varies regionally over the continent. The following discussion summarises the results and suggests some implications of a changing fire regime on five specific eco-regions in Australia by drawing on the basic response of ecosystems to fire regimes (e.g., Gill, 1983). Other impacts of CO_2 relevant to fire regimes, but not included in the fire danger index, are also discussed (for example increased frequency of lightning strikes or the response of vegetation to increased CO_2).

Changes in FDI can be extended to changes in fire behaviour using the empirical relationships between FDI and fire behaviour defined as part of the FDI (McArthur, 1966, 1967). In the fire season control scenario at Sale and Hobart approximately 5% of daily FDIs are in the 'very high' (FDI between 24 and 50) and 'extreme' (FDI greater than 50) categories. This rate of occurrence in the doubled CO_2 scenario increases slightly to 7% at Hobart but triples to 15% at Sale. The consequential impacts on forests depend on the fuel quantity. In forests with fuel levels around 25 t/ha, and using the less severe scenario of an FDI of 25, typical fire intensity will be around 10×10^3 kW/m where the rate of spread is approximately 0.8 km/h, the spotting distance 2.1 kms, and the flame height inducive for crown fires. If the FDI is 50, then the rate of spread nearly doubles to reach 1.5 km/h and the spotting distance increases to 4.6 km. Fires of such high intensity have the ability to destroy the canopy in addition to understorey material, and in extreme cases kill trees. Fires of lower intensity may only remove the litter layer and fine fuels and kill the understorey.

The impact on the south-west forest region is represented by the doubled CO_2 simulation at grid point (2,4)/Katanning. The only fire weather parameter that has a significant change is temperature, which increases. The length of the fire season does not change but the period of greatest severity occurs at the end rather than the beginning of the season. The season is more severe. Nearly half of the days in the fire season have 'very high' or 'extreme' fire danger, with the occurrence of 'extreme' conditions doubling.

The Victorian mallee region (gridpoint (6,4)) has a Mediterranean-type climate of winter-dominated rainfall and is characterised by scleromorphic shrublands of multi-stemmed eucalypts along with spinifex and porcupine grasses (Noble et al., 1980). It is highly prone to fire. As in other less arid southern regions, the mean fire season temperatures increase by 4 °C, seasonal rainfall increases and daily minimum relative humidity decreases. Wind speed changes little. These changes in individual fire weather variables each have a different effect on fire danger. Fire danger is most sensitive to the changes in temperature and seasonal rainfall.

The seasonal fire danger increases throughout the region, and there are many more occurrences of 'extreme' FDI. The length of the fire season is shortened and the month of greatest fire danger occurs earlier in the season. Even though the fire season becomes shorter there are nearly twice as many 'very high' and 'extreme' FDI occurrences. In contrast to the situation of the more southern regions which may experience a longer fire season, the scenario for the Mallee indicates the fire season becoming shorter and more severe.

The wet-dry tropics cover the northern and north-eastern region of Australia extending from Broome in the west to Brisbane in the east (Gill et al., 1990). At the two grid points representing the area, the fire season conditions become warmer and less humid (humidity decreases more at Miles than at Normanton), and less windy. The changes in seasonal rainfall vary regionally with the north receiving more rain and the south less. Changes in fire danger are mainly due to changes in rainfall.

There are many more occurrences of extreme conditions in the north (little change in extreme occurrences in the south), but the change in overall fire season severity is greatest in the southern reaches of the zone. Although the length of the fire season is not projected to change, the seasonality of the fire season is changed with greatest severity occurring earlier in the season. The southern section of the zone has a slightly later fire season than the north. The mean state of the season's severity does not exceed that of the existing variability.

The central Australian rangelands near Alice Springs are in Australia's arid zone. Most of the annual rainfall of 260 mm (Alice Springs) occurs in summer and is very erratic. Most fires occur in the period from October to January, and range from 10 to 13,000 km^2 in size. 59% of fires from 1970 to 1980 were due to lightning, with the spinifex area having up to 66% of fires attributed to lightning (Griffin et al., 1983). The CSIRO9 results at grid point (5,7)/Alice Springs are used to represent the region, specifically with respect to potential changes in the fire danger of the region. The doubled CO_2 scenario does not indicate large changes in seasonal rainfall, only small increases. Other changes in fire weather include an increase in mean temperature, mean relative humidity decreases, and significant decreases in wind speed. Although the changes in seasonal rainfall are very small compared with changes to other fire weather variables, fire danger is most responsive to rainfall changes. The fire season is longer, more severe, and the bi-modal nature of the season is even more pronounced. The mean seasonal fire danger increases.

The seasonal distribution of thunder days is strongly correlated with that of bushfire incidence ($r = 0.94$) (Griffin et al., 1983). 'Dry' thunderstorms are a feature of inland Australia, and according to the modelling of Price and Rind (1991), activity in this region is likely to increase in an increased CO_2 climate (for their particular scenario and model). Combining this suggested increase in lightning activity with the projected increase in seasonal fire danger at Alice Springs (the season becomes longer and has a 50% increase in the number of higher fire danger days) the effect of global warming on fire danger is likely to be even more significant.

6. Conclusions

Due to the close correlations between climate and fire activity, the climatically-based FDI is an appropriate measure by which potential changes in the fire weather regime can be estimated. The doubled-CO_2 fire danger scenario has therefore been analysed for changes in seasonality, daily variability, seasonal variability, and sensitivity to changes in each of the fire weather variables. To assess the relative nature of the changes in FDI, comparisons were made with the current observed extreme FDI range.

The control simulation of some of the fire weather parameters, especially minimum relative humidity and wind speed, has an existing bias that most likely influences the $2 \times CO_2$ results. Interpretation of the fire danger simulation must include an understanding of the limitations of the scenarios by recognition of the assumptions that are built into the GCM and that are used for determining model verification and validation. Some of the implications of this research are broad and applicable to the entire continent of Australia, and others may be single site specific.

The consequent seasonal fire danger scenarios for the northern and southern seasons have much significance. In a doubled-CO_2 climate simulation, Alice Springs, Miles, Sale, and Mildura all have significant changes in the probability distribution of daily FDI, and the seasonal ΣFDI increases throughout both the Northern and Southern fire zones. This effect has also been seen in boreal studies (Stocks et al., 1998). The seasonal ΣFDI is most sensitive to the large changes in temperature. The seasonality of fire danger is also affected, but the degree of change varies widely. Of the eight detailed sites, only at Katanning and Hobart does the length of the fire season not change.

References

Allen-Diaz, B.: 1996, 'Rangelands in a Changing Climate: Impacts, Adaptations and Mitigation', in Watson, R. T., Zinyowera, M. C., and Moss, R. H. (eds.), *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change*, Cambridge University Press, U.K., pp. 131–158.

Beer, T. and Williams, A. A. J.: 1995, 'Estimating Australian Forest Fire Danger under Conditions of Doubled Carbon Dioxide Concentrations', *Clim. Change* **29**, 169–188.

Bergeron, J. and Flannigan M. D.: 1995, 'Predicting the Effects of Climate Change on Fire Frequency in the Southern Canadian Boreal Forest', *Water Air Soil Pollut.* **82**, 437–444.

Bessie, W. C. and Johnson, E. A.: 1995, 'The Relative Importance of Fuels and Weather on Fire Behaviour on Sub-Alpine Forests', *Ecology* **76**, 747–762.

Flannigan, M. D. and Van Wagner, C. E.: 1991, 'Climate Change and Wildfire in Canada', *Can. J. Forest Res.* **21**, 66–72.

Fosberg, M. A., Stocks, B. J., and Lynham, T. J.: 1996, 'Risk Analysis in Strategic Planning: Fire and Climate Change in the Boreal Forest', in Goldammer, J. C. and Furyaev, V. V. (eds.), *Fire in Ecosystems of Boreal Eurasia*, Kluwer Academic Publishers, Dordrecht, pp. 495–505.

Gill, A. M.: 1983, 'Forest Fire and Drought in Eastern Australia', in *Proceedings of a Symposium on the Significance of El-Niño Southern Oscillation Phenomena and the Need for a Comprehensive Ocean Monitoring System for Australia*, 27 and 28 July, Canberra, Australia.

Gill, A. M., Hoare, J. R. L., and Cheney, N. P.: 1990, 'Fires and their Effects in the Wet-Dry Tropics of Australia', in Goldammer, J. G. (ed.), *Fire in the Tropical Biota*, Springer-Verlag, p. 497.

Griffin, G. F., Price, N. F., and Portlock, H. F.: 1983, 'Wildfires in Central Australia', *J. Environ. Manage.* 17, 311–323.

IPCC, Intergovernmental Panel on Climate Change: 1996, *Climate Change 1995: The Science of Climate Change*, Houghton, J. T., Meira Filho, L. G., Callender, B. A., Harris, N., Kattenberg, A., and Maskell, K. (eds.), Cambridge University Press, U.K., p. 572.

Keetch, J. J. and Byram, G. M.: 1968, *A Drought Index for Forest Fire Control*, Research Paper E38, U.S. Department of Agriculture-Forest Service, Asheville, N.C., p. 32.

Kirschbaum, M. U. F. and Fischlin, A.: 1996, 'Climate Change Impacts on Forests', in Watson, R. T., Zinyowera, M. C., and Moss, R. H. (eds.), *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change*, Cambridge University Press, pp. 95–130.

McArthur, A. G.: 1966. 'Weather and Grassland Fire Behaviour', *Comm. Aust. Timb. Bur. Leaflet* **100**, 23.

McArthur, A. G.: 1967, 'Fire Behaviour in Eucalypt Forest', *Comm. Aust. Timb. Bur. Leaflet* **107**, 25.

McGregor, J. L., Gordon, H. B., Watterson, I. G., Dix, M. R., and Rotstayn, L. D.: 1993, *The CSIRO 9-Level Atmospheric General Circulation Model*, CSIRO Division of Atmospheric Research, Technical Paper No. 26, CSIRO, Australia, p. 89.

Noble, I. R., Barry, G. A. V., and Gill, A. M.: 1980, 'McArthur's Fire-Danger Meters Expressed as Equations', *Aust. J. Ecol.* **5**, 201–203.

Noble, J. C., Smith, A. W., and Leslie, H. W.: 1980, 'Fire in the Mallee Shrublands of Western New South Wales', *Aust. Rangel. J.* **2**, 104–114.

Price, C. and Rind, C.: 1991, 'Lightning Activity in a Greenhouse World', in *Proceedings of the 11th Conference on Fire and Forest Meteorology*, 16–19 April 1991, Missoula, Montana, U.S.A., The Society of American Foresters, pp. 598–604.

Price, C. and Rind, C.: 1994, 'Possible Implications of Global Climate Change on Global Lightning Distributions and Frequencies', *J. Geophys. Res.* **99**, 10823.

Stocker, G. C. and Mott, J. J.: 1981, 'Fire in the Tropical Forests', in Gill, A. M., Groves, R. H., and Noble, I. R. (eds.), *Fire and the Australian Biota*, Australian Academy of Science, Canberra, pp. 427–433.

Stocks, B. J., Fosberg, M. A., Lynham, T. J., Mearns, L., Wotton, B. M., Yang, Q., Zin, J-Z., Lawrence, K., Hartley, G. R., Mason, J. A., and McKenney, D. W.: 1998, 'Climate Change and Forest Fire Potential in Russia and Canadian Boreal Forests', *Clim. Change* **38**, 1–13.

Swetnam, T. W.: 1993, 'Fire History and Climate Change in Giant Sequoia Groves', *Science* **262**, 885–889.

Takle, E. S., Bramer, D. J., Heilman, W. E., and Thompson, M. R.: 1994, 'A Synoptic Climatology for Forest Fires in the NE U.S. and Future Implications from GCM Simulations', *Int. J. Wildland Fire* **4**, 217–224.

Trabaud, L. V., Christensen, N. L., and Gill, A. M.: 1993, 'Fire Biogeography: Temperate and Mediterranean', in Crutzen, P. J. and Goldammer, J. G. (eds.), *Fire in the Environment: The Ecological, Atmospheric and Climatic Importance of Vegetation Fire*, Wiley.

Watterson, I. G., Dix, M. R., Gordon, H. B., and McGregor, J. L.: 1995, 'The CSIRO Nine-Level Atmospheric General Circulation Model and Its Equilibrium Present and Doubled CO_2 Climates', *Aust. Met. Mag.* **44**, 111–125.

Webb, L. J.: 1958, 'Cyclones as an Ecological Factor in Tropical Lowland Rainforest, North Queensland', *Aust. J. Bot.* **6**, 220–228.

Whetton, P. H., Mullan, A. B., and Pittock, A. B.: 1996, 'Climate Change Scenarios for Australia and New Zealand', in Pearman et al. (eds.), *Coping with Climate Change*, CSIRO, Australia, pp. 145–168.

Williams, A. A. J. and Karoly, D. J.: 1999, 'Extreme Fire Weather in Australia and the Impact of the El Niño-Southern Oscillation', *Aust. Met. Mag.* **48**, 15–22.

(Received 31 March 1998; in revised form 31 July 2000)