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CSIRO Submission 09/345

Climate Change and the 2009 Bushfires

Prepared for the 2009 Victorian Bushfires Royal Commission

May 2009

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Important Notice

Terms of Reference

The full terms of reference of the 2009 Victorian Bushfires Royal Commission ("Royal Commission") are available at www.royalcommission.vic.gov.au and include inquiring into and reporting on the following matters:

1. The causes and circumstances of the bushfires which burned in various parts of Victorian in late January and in February 2009 ("2009 Bushfires").

2. The preparation and planning by governments, emergency services, other entities, the community and households for bushfires in Victoria, including current laws, policies, practices, resources and strategies for the prevention, identification, evaluation, management and communication of bushfire threats and risks.

3. All aspects of the response to the 2009 Bushfires, particularly measures taken to control the spread of fires and measures taken to protect life and private and public property, including but not limited to:
   (a) immediate management, response and recovery;
   (b) resourcing, overall coordination and deployment; and
   (c) equipment and communication systems.

4. The measures taken to prevent or minimise disruption to the supply of essential services such as power and water during the 2009 Bushfires.

5. Any other matters that you deem appropriate in relation to the 2009 Bushfires.

Recommendations arising out of the inquiry considered appropriate, including recommendations for governments, emergency services, other entities and the community on:

6. The preparation and planning for future bushfire threats and risks, particularly the prevention of loss of life.

7. Land use planning and management, including urban and regional planning.

8. The fireproofing of housing and other buildings, including the materials used in construction.

9. The emergency response to bushfires.

10. Public communication and community advice systems and strategies.

11. Training, infrastructure, and overall resourcing needs.

CSIRO's response to the Terms of Reference

CSIRO is providing information to the 2009 Victorian Bushfires Royal Commission in three ways:

a) Fire behaviour during the 2009 Bushfires – CSIRO is contributing to a report being prepared for the Royal Commission by the Bushfire CRC,
b) Buildings and planning – a separate CSIRO led report to the Royal Commission has been proposed on these issues, and
c) Climate change and the 2009 Bushfires – this submission.

The submission was prepared pursuant to a request by Ms Melinda Richards, Counsel Assisting the Royal Commission in discussions with Dr Andrew Johnson (Group Executive Environment, CSIRO). The submission focuses particularly on issues related to bushfires and climate change which are not being covered by the Bushfire CRC's report on fire behaviour during the 2009 Victorian Bushfires (to which CSIRO is also contributing).

This submission is prepared solely to assist the Royal Commission in its inquiries pursuant to the Terms of Reference and may only be used for that purpose. Any extracts of the submission distributed for these purposes must clearly note that the extract is part of a larger submission prepared by CSIRO for the Royal Commission. The submission cannot be used for any other purposes (including for the purposes of endorsements or litigation) without the prior consent of CSIRO.

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Contents

Acronyms Used

BoM	Bureau of Meteorology
CAWCR	Centre for Australian Weather and Climate Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CO2-e	Carbon dioxide equivalent
CRC	Cooperative Research Centre
DF	Drought Factor
DMI	Dipole mode index
FDI	Fire danger index
FFDI	Forest fire danger index
FFDM	Forest fire danger meter
GFDI	Grassland fire danger index
GFDM	Grassland fire danger meter
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
pIOD	Positive Indian Ocean Dipole
ppm	Parts per million
R&D	Research and Development
STR	Sub-tropical ridge
UNFCCC	United Nations Framework Convention on Climate Change

Executive Summary

This submission focuses on:
1. links between climate change, bushfire weather and fuel management, in particular the conditions experienced during the 2009 Bushfires and
2. opportunities for consideration of climate change to improve preparation and planning to reduce future bushfire risk.

Bushfires are an inevitable occurrence in Australia. Fire is most common over the tropical savannas of the north, however the southeast, where the majority of the population resides, is susceptible to large wildfires that threaten life and property. A unique factor in these southeastern fires is the Mediterranean climate of the region. This normal risk is exacerbated by periodic droughts that occur as a part of natural interannual climate variability.

The relationship between climate change and bushfires in south-eastern Australia is complex, multi-faceted and only beginning to be understood. To assess the influence of natural climate variability and anthropogenic climate change on bushfires in forested regions of Victoria, we need to consider temperature, rainfall, relative humidity, wind speed, and forest fuel.

Section 1 of this submission outlines current scientific understanding about each of these factors, and explores projections of climate change impacts on future fire weather.

Temperature
The high temperatures and which contributed to the extreme fire weather conditions and high fuel hazard in Victoria in late January and early February 2009 are part of ongoing climate trends observed in the region over the last 50 or more years. These trends translate into an increased risk of extreme fire conditions. Regarding temperature, there has been no specific study of the link between Victorian heatwaves and anthropogenic climate change, but the observed increase in the frequency and magnitude of very hot days in Australia is mostly due to anthropogenic increases in greenhouse gas emissions.

Rainfall
The low rainfall in Victoria in January and early February 2009 further reinforced 12-year rainfall deficits in much of south-eastern Australia. This is also part of a 50-year drying trend over most of eastern Australia which translates into increased extreme fire condition risk. This record dryness may be due to natural variability, and formal attribution studies have not been completed, but there are indications that it may also be partly due to anthropogenic climate change.

Humidity
The extremely low relative humidity on 7 February 2009 was associated with the record low rainfall in January 2009 and the heatwave that started in late January 2009. A study by the Bushfire CRC is underway to determine observed trends in relative humidity, so it is not yet possible to say whether any trends are linked to anthropogenic climate change. However, relative humidity is projected to decrease with projected climate change in Australia due to anthropogenic increases in greenhouse gases.

Wind
It is clear that high wind speeds played an important role in the 2009 Bushfires, as they have in other major bushfires in Victoria in the past. No studies have been undertaken to assess whether changes in Australian wind-speed are linked to anthropogenic climate change.

Forest fuel
In relation to climate change and forest fuels - on the one hand, elevated carbon dioxide levels may enhance vegetation production and thereby increase fuel loads, however drought conditions may decrease long-term vegetation production (and fuels) and may decrease fuel moisture (thereby increasing potential rates of spread). The implications for fire behaviour will be complex, since there may also be concurrent changes in fire regimes (i.e. the pattern of recurrence of fires across the landscape) and land management practices. This is a developing research area, and no specific studies have been done into the influence of climate change on forest fuels in Victoria.

Projections for the future
CSIRO's climate modelling can provide projections of how climate change may influence the occurance of high fire danger weather conditions in future decades. A modelling study in south-eastern Australia found that the simulated annual-average number of days with 'Extreme' fire danger increases by 5-25% by 2020, relative to 1990, for a low rate of global warming. For a high rate of global warming, the number of 'Extreme' days increases by 15-65% by 2020. By 2050, the number of 'Extreme' days increases by 10-50% for low global warming and by 100-300% for high global warming.

'Catastrophic' fire-weather occurred on 16 Feb 1983 (Ash Wednesday), 18 Jan 2003 (Canberra fire) and 7 Feb 2009 (Black Saturday). Only 12 of the 26 sites analysed in south-eastern Australia have recorded 'Catastrophic' fire-weather days since 1973. By 2020 for high global warming, 'Catastrophic' fire-weather days are predicted to occur at 20 sites, 10 of which have return periods of around 16 years or less. By 2050 for high global warming, 'Catastrophic' days are predicted to occur at 22 sites, 19 of which have return periods of around 8 years or less, while 7 sites have return periods of 3 years or less.

Section 2 of this submission identifies six areas where research taking climate change into account could improve preparation and planning for future bushfire threats and risks. These are:

i) Forest Fire Danger Index
The FFDI has been used for many decades. By preserving the method of determining fire danger, using forest and grassland fire danger indices, continuity with historical data is provided that enables fire authorities to benchmark response levels and to compare fire weather occurrences. However, with the likely onset of climate change effects, aspects of the FFDI, particularly the assumptions regarding the rate of fuel drying may need to be revised to better reflect the change in drying conditions in future.

ii) Climate change, fuel hazard and fire behaviour
While the impact of changed climate is likely to be an increase in the frequency of 'Extreme' fire danger days, the impact of climate change on the structure of the forest, fuel availability and thus the behaviour of bushfires is not known. Changes in species composition and thus structure are likely under sustained changed climate, but the rate of change and the type of change is unknown.

iii) Fuel hazard reduction burning
With the projected warmer and drier conditions due to climate change and the subsequent increase in the number of days of extreme fire weather, it is expected that current 'windows' for applying prescriptions of hazard reduction burning will change and possibly narrow. This means less opportunity to conduct safe and effective hazard reduction burns. This will require reassessment of the current operational limits (i.e. work hours, smoke levels, etc) of conducting hazard reduction burning.

iv) Bushfire suppression and control
Under projected climate conditions, in which the number of days of 'Extreme' fire weather is expected to increase for much of south-eastern Australia, improving the success of initial response to fire will be critical to ensuring large conflagration fires do not develop. Fire management practices and management of fuel hazard need to be as efficient and as effective as possible to aid success.

v) House loss risk index
There is potential to develop an improved house loss risk index to better inform communities of the potential for a fire under given fire weather conditions to cause life and property loss. It is proposed that issues related to buildings and planning be dealt with in detail in a separate CSIRO report to the Royal Commission.

vi) Enhanced fire weather projections

Enhanced fire weather modelling could improve long-term strategic planning for future bushfires. This would involve evaluating the performance of a number of global and regional models against historical data, selecting the better models for generating projections, and analysing the output in ways that are relevant to fire management agencies. There is potential to enhance the CSIRO-Bureau of Meteorology ACCESS model to include a fire module, linked to a dynamic vegetation model (CABLE). This could provide seasonal and multi-decadal fire weather forecasts.

Introduction

CSIRO is an internationally recognised research and development (R&D) provider in the fields of climate change and bushfires. CSIRO has conducted research relevant to this Royal Commission in areas including climate modelling and climate forecasting as well as fuel dynamics, fire weather, combustion dynamics, fire behaviour modelling, fire ecology and fire management.

This submission has been prepared by a team of scientists from CSIRO with experience and international recognition in many facets of climate change and bushfire research. The submission focuses particularly on issues related to bushfires and climate change. It does not include work on fire behaviour during the 2009 Bushfires that is being carried out by the Bushfire CRC and to which CSIRO is also contributing. However, it does briefly discuss general issues of fire behaviour and climate change. It discusses CSIRO's current understanding of fire in the Australian landscape, and indicates some key areas where further research could enhance the capacity to respond to bushfire risks in the future.

Issues of fire and climate change

Bushfires are an inevitable occurrence in Australia. With more than 800 endemic eucalypt species, Australian vegetation over much of the medium-high rainfall regions of the continent is dominated by these fire-adapted species. Fire is most common over the tropical savannas of the north, where some parts of the land burn on an annual basis. However, the southeast, where the majority of the population resides, is susceptible to large wildfires that threaten life and property.

A unique factor in these fires of the southeast is the climate of the region. The southeast experiences a so-called Mediterranean climate, with hot, dry summers and mild, wet winters. The winter and spring rains allow fuel growth, while the dry summers allow fire danger to build. This normal risk is exacerbated by periodic droughts that occur as a part of natural interannual climate variability.

The relationship between climate change and bushfires in south-eastern Australia is complex, multi-faceted and only beginning to be understood. Figure 1 below provides a conceptual diagram of the relationship between climate change and bushfires.

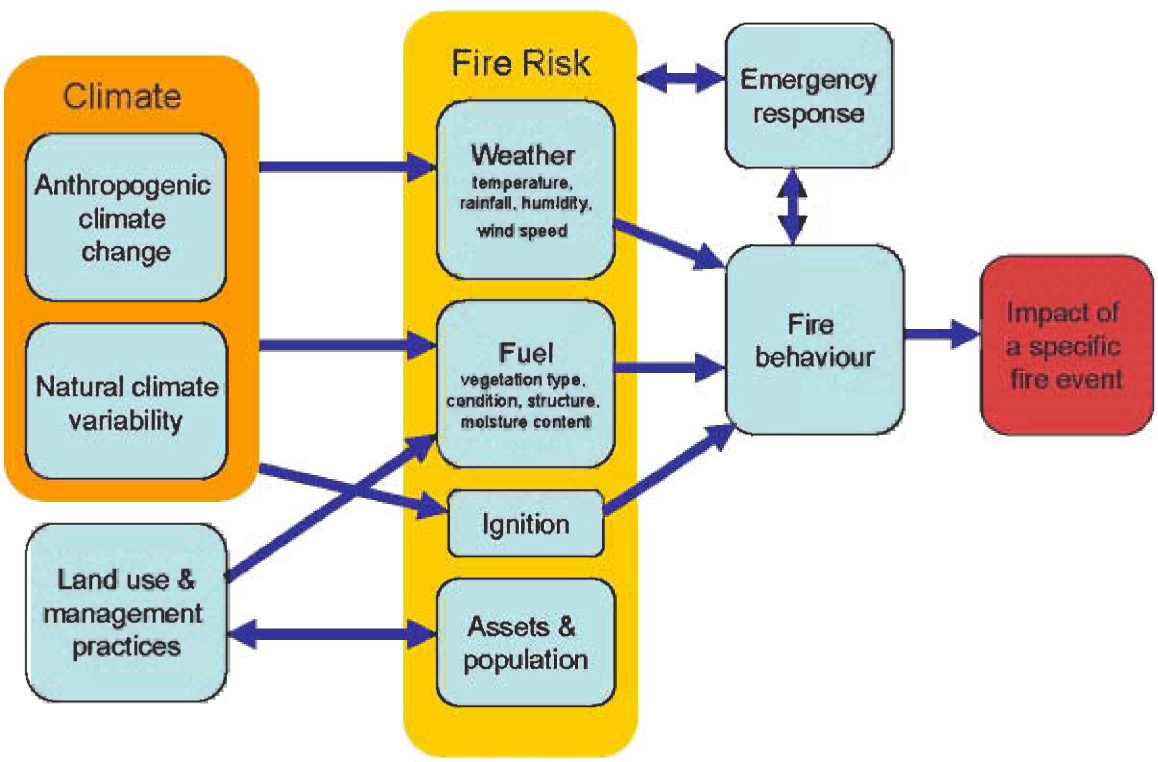

Figure 1: Conceptual diagram of the link between climate change and bushfires

Based on our current scientific understanding, climate change is likely to influence a number of aspects of bushfire risk, behaviour and management at different time-scales. In particular, climate change may affect:

- The occurrence of high-risk fire weather conditions;
- The characteristics of the natural vegetation which provides fuel for fires;
- The effectiveness of existing tools, strategies and approaches for managing and controlling bushfires.

1. Climate change and bushfire weather

(i) Global observations of climate change

An outline of the 'Science of Climate Change' prepared for a CSIRO briefing given at Parliament House, Canberra on 16 March 2009 is attached in Appendix 2.

The consequences of human induced climate change are a current research focus around the world. The Intergovernmental Panel on Climate Change (IPCC) was created in 1988 to assess information relevant to understanding the risk of human-induced climate change. It has produced four assessment reports (1990, 1995, 2001 and 2007). Key conclusions of the latest report (IPCC 2007) are:

- Warming of the climate system is unequivocal,
- Most of the observed increases in globally averaged temperatures since the mid-20th century is very likely (greater than 90 percent likelihood) due to the observed increases in anthropogenic (human) greenhouse gas concentrations, and
- Anthropogenic warming and sea level rise would continue for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized.

An international scientific congress on 'Climate Change: Global Risks, Challenges & Decisions' held in Copenhagen in March 2009 was attended by more than 2,500 delegates from nearly 80 countries and reviewed the latest evidence. Recent observations confirm that the worst-case scenario trajectories for factors such as global warming and sea level rise presented in previous IPCC assessment reports, including the 2007 report, are being realised (Rahmstorf et al. 2007).

(ii) Weather conditions before and during the 2009 Bushfires

Was climate change a contributing factor to the fire conditions experienced in early February 2009? To answer this question, consideration needs to be given to the factors that affect fire weather, namely high temperatures, low rainfall, low relative humidity and high wind-speeds. These are the factors are used to determine the Forest Fire Danger Index (FFDI).

High temperatures

The Bureau of Meteorology (BoM, 2009) has assessed the exceptional January-February 2009 heatwave in south-eastern Australia. The conditions from 28 to 30 January set many individual-day and multi day records (http://www.bom.gov.au/climate/current/statements/scs17c.pdf). A weak change brought some relief to southern coastal areas after 31 January, but inland areas remained very hot until 5 February. Extreme heat then returned, peaking on 7 February when record high temperatures were set across most of Victoria.

These extremely high temperatures are part of a global warming trend. Most of the global warming observed over the past 50 years is very likely (at least 90% likelihood) due to anthropogenic increases in greenhouse gas emissions (IPCC, 2007). It is very likely that this is not due to natural variability alone (IPCC, 2007). Discernible human influences extend to continental-average temperatures and temperature extremes (IPCC, 2007). It is more likely than not (at least 50% likelihood) that human activities have increased the risk of heat waves (IPCC, 2007). Australian-average temperatures have increased by 0.9°C since 1950 (CSIRO and BoM, 2007) (Figure 2). Since 1950, Victoria's maximum temperature has risen 0.8°C (Figure 3) (Vic DSE, 2008). The warmest year on record in Victoria was 2007 (BoM, 2008). The warming in Australia has been associated with a significant increase in the frequency of extremely high temperatures and heat waves (Alexander and Arblaster, 2009). Increases in mean and maximum temperature in Australia since 1950 have been mostly attributed to anthropogenic climate change (Karoly and Braganza, 2005). While there has been no specific study of the link between Victorian heatwaves and anthropogenic climate change, the observed rise in maximum temperature (mostly due to anthropogenic climate change) is likely to have increased the risk of heatwaves in Victoria.

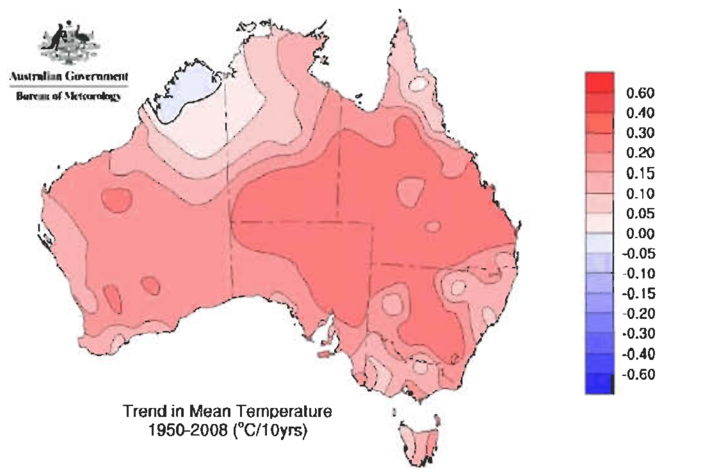

Figure 2: Trend in mean temperature from 1950-2008 (°C per decade). Source: http://www.bom.gov.au/cgi-bin/climate/change/trendmaps.cgi

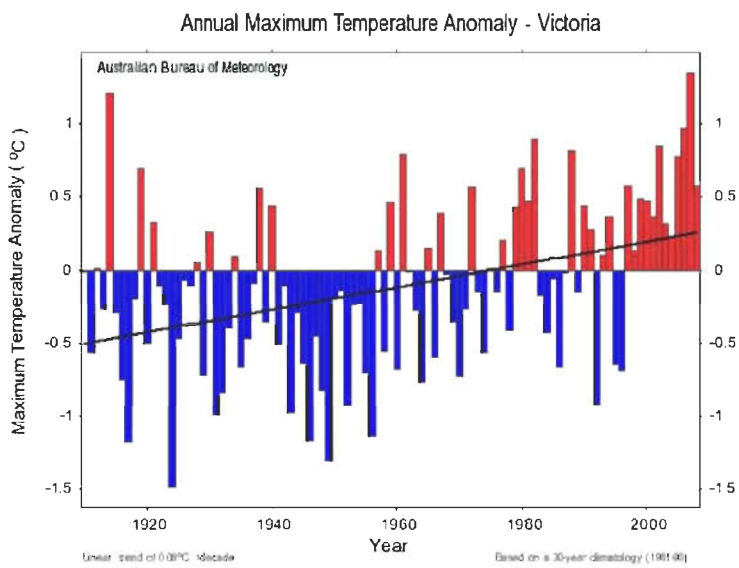

Figure 3: Victorian annual maximum temperature anomalies from 1910-2008, relative to the average for 1961-1990. http://www.bom.gov.au/cgi-bin/climate/change/timeseries.cgi

Recent CSIRO research (Cai et al. 2009) suggests that there is a link between the 2009 Bushfires and the Indian Ocean Dipole (IOD). A positive IOD (pIOD) event refers to a state in which the eastern Indian Ocean is cooler than normal, accompanied by anomalous warming in the western Indian Ocean. A pIOD contributes to lower rainfall and higher temperatures in the spring season over Victoria exacerbating the dry conditions and increasing the fuel load going into summer. For Victoria, spring is the main rainfall season, with summer being the driest season.

As such, pIODs are quite effective in preconditioning Victoria bushfires, more so than El Niño events. Of the 21 significant bushfires[1] that have occurred since 1950, 11 were preceded by a pIOD event (Figure 4), out of a total of 16 pIODs.

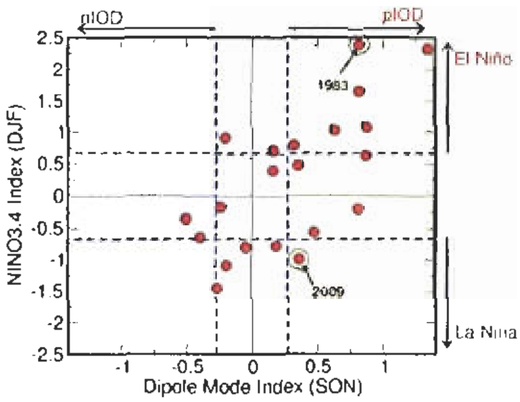

Figure 4: Scatterplot of significant Victorian summer bushfires[1] (red dots) from 1950-2009 in terms of the preceding Indian Ocean Dipole (IOD) and concurrent El Niño-Southern Oscillation (ENSO) conditions. The IOD is shown by a dipole mode index (DMI) in spring (September, October, and November, or SON), and ENSO by the NINO3.4 index in summer (December, January, and February, or DJF). An El Niño or pIOD is defined when these indices exceed 0.75 of their long-term standard deviation, indicated by areas outside the blue dashed lines (Cai et al., 2009).

During the past 50 years, consistent mean circulation changes have emerged in the tropical Indian Ocean, trending towards a warming pattern reminiscent of a pIOD state (Cai et al. 2009), as projected by global climate models (Vecchi and Sodon, 2007). These changes are accompanied by a steadily increased frequency in occurrence of pIOD events, from less than four events per 30 years early in the 20th century, to over 10 during the last 30 years. In contrast, over the same time-frame the number of negative IOD (nIOD) events decreased from over 10 to two per 30 years. The Indian Ocean has experienced a pIOD event in five out of the past seven years, including a set of arguably unprecedented three-consecutive events during 2006-2008, contributing to the severe drought over southeast Australia during the past decade (Cai et al., 2009).

These results suggest that climate change will increase the occurrences of pIOD events. Therefore, there is some evidence that climate change will increase the bushfire risk across Victoria, as a consequence of the Indian Ocean's response to global warming, in addition to any impact from rising temperatures.

Low rainfall

Victoria was very dry in the weeks prior to 7 February 2009. Melbourne had no measurable rain from 4 January to 7 February, the equal second-longest dry spell on record for the city (BoM, 2009). A number of locations around Melbourne, as well as Ballarat, set new January records for low rainfall. Many places north and west of Melbourne had no rain in January, including Swan Hill, Nhill, Stawell, Bendigo, Yarrawonga, Heathcote and Maryborough (BoM, 2009). These dry conditions further reinforced 12-year rainfall deficits in much of south-eastern Australia. The area of record low 12-year totals (Figure 5) covers the majority of southern Victoria from Gippsland westwards, extending into South Australia. This is part of a 50-year drying trend over most of eastern Australia.

[1] A historical list of significant Australian bushfires are tabled in Ellis et al. 2004 (bushfires from 2004 onwards are taken from the Country Fire Authority (CFA) database listed at http://www.cfa.vic.gov.au/about/history/majorfires.htm)

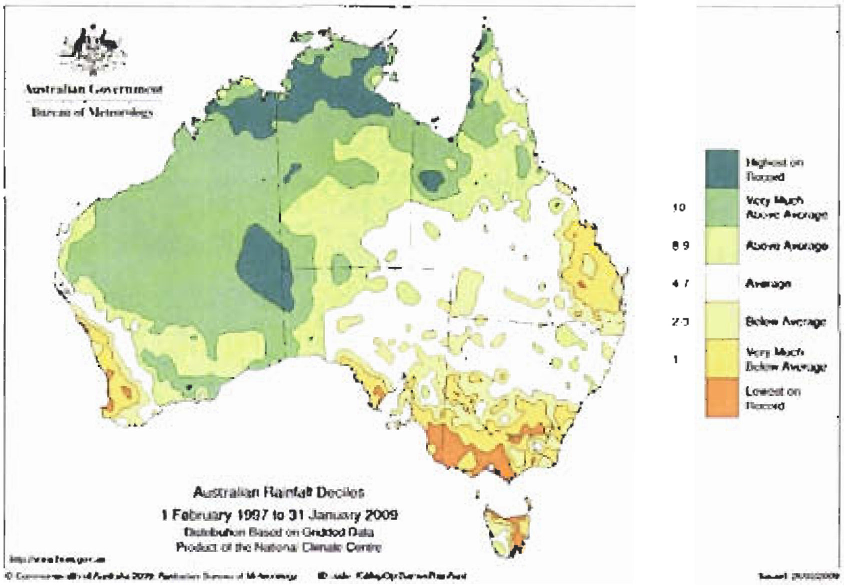

Figure 5: Rainfall deciles for the 12-year period Feb 1997 to Jan 2009.

This record dryness may be due to natural variability, but may also be partly due to anthropogenic climate change. It is still too early to tell because formal attribution studies have not been completed. However, initial results from the South East Australian Climate Initiative (Timbal et al, 2007) indicate that "the intensity of the sub-tropical ridge (STR) has been trending upward since the 1970s and that can be translated into a sizeable rainfall decline (about 70% of the observed decline in autumn to early winter: from March to July) using the correlation between the STR intensity and rainfall in south-east Australia. By and large during the 20th century, the long-term evolution of the intensity of the STR follows the curve of the global temperature of the planet. This relationship gives a high likelihood that the current rainfall deficit is linked to the global warming of the planet, through the intensification of the STR". Therefore, the very low rainfall in Victoria preceding 7 February 2009 may be partly due to anthropogenic climate change.

Low relative humidity

The extremely low relative humidity on 7 February 2009 (around 5%) is associated with the record low rainfall in January 2009 and the heatwave that started in late January 2009. A study by the Bushfire CRC is underway to determine observed trends in relative humidity, so it is not yet possible to say whether any trends are linked to anthropogenic climate change. However, relative humidity is projected to decrease with projected climate change in Australia due to anthropogenic increases in greenhouse gases (CSIRO and BoM, 2007).

High wind-speeds

High wind speeds around 5 pm on 7 February preceded the passage of a cold front, bringing hot and dry air from central Australia. This typically occurs with major fires in Victoria, such as Ash Wednesday (Lucas et al., 2007). While annual mean wind-speeds have been decreasing over much of Australia since 1957 (McVicar et al., 2008), there has been a small increase over southern central Victoria (Figure 6). No studies have been undertaken to assess whether changes in Australian wind-speed are linked to anthropogenic climate change.

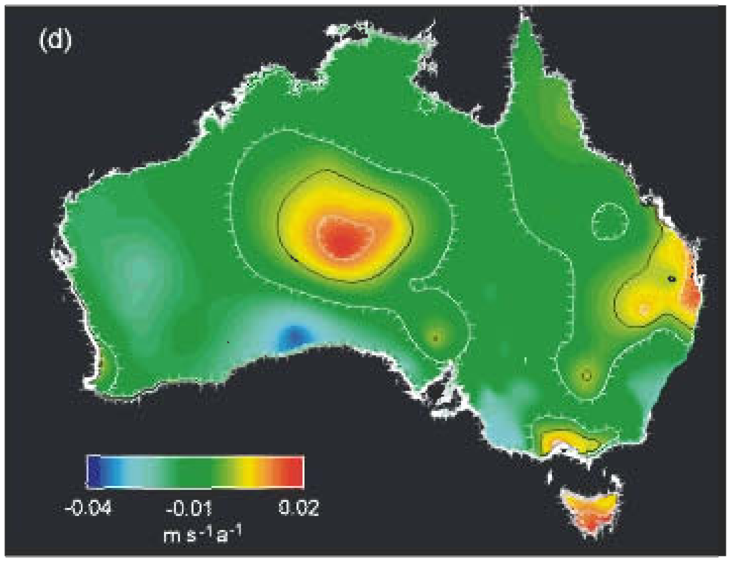

Figure 6: Wind-speed trends from 1975-2006. Black lines show no change and white lines show significant trends with barbs pointing to increased significance. Source: McVicar et al. (2008).

The Forest Fire Danger Index

The McArthur forest fire danger index (FFDI) is based on temperature, rainfall (expressed as a drought factor), humidity and wind speed – the four factors described above. Both the forest fire danger index and the grassland fire danger index (GFDI) are described in greater detail in Section 2.

When the FFDI is 25-50, the risk rating is 'Very High'. When the FFDI is greater than 50 the risk rating is 'Extreme' and a 'Total Fire Ban' is usually declared. The Black Friday bushfires of 1939 were used as an example of a 100 rating on the scale. During the 2009 Bushfires, the index reached well over 100 at many locations.

There is a 35 year trend of an increasing annual total FFDI for south-eastern Australia. Research undertaken by CSIRO and the Bureau of Meteorology, through the Centre for Australian Weather and Climate Research (CAWCR) and the Bushfire CRC, found that the annual total FFDI displays a rapid increase in the late-1990s to early-2000s at many locations (Lucas et al., 2007). Increases of 10-40% between the average level for 1980-2000 and the average level for 2001-2007 are evident at most sites. The increases are associated with a jump in the number of 'Very High' and 'Extreme' fire danger days. Increasing trends in annual total FFDI for four Victorian sites with high quality data are shown in Figure 7. Hence, the extremely high FFDI values on 7 February 2009 represent a continuation of an increasing trend in the FFDI.

While FFDI is an important element in understanding fire weather, it must be considered in the context of other factors such as fire management and fuel load, as discussed in the next section.

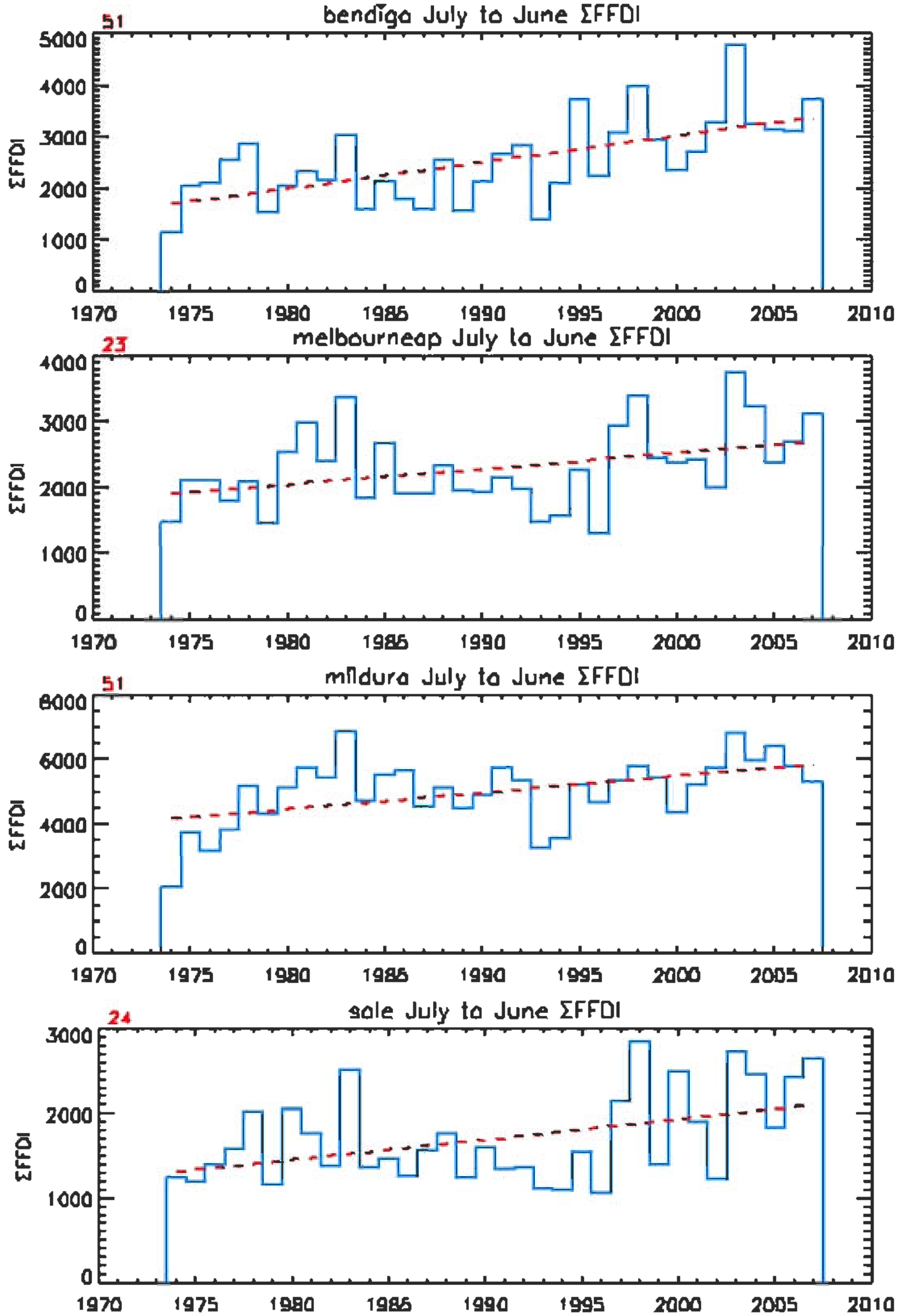

Figure 6: Annual total FFDI (sum of daily 3 pm values, from July to June) at Bendigo, Melbourne airport, Mildura and Sale from 1973-2007. The magnitude of the linear trend is the red number at top left (FFDI units per year). Source: Lucas et al (2007).

(iii) Potential changes in future fire weather risk

Future climate change will depend to some extent on the effectiveness of domestic and international efforts to control greenhouse gas emissions. There are concerted efforts through current international negotiations to seek to stabilise atmospheric carbon dioxide equivalent (CO2-e) concentrations (including the effect of all greenhouse gases) between 450 and 550 parts per million (ppm) by mid century. However, significant climatic changes are predicted to take place even if CO2-e concentrations can be stabilised below 550 ppm (IPCC 2007).

CSIRO has contributed to projections of climate change for Australia (CSIRO and BoM 2007). Projections for Victoria indicate a warming climate with increases in extremely high temperatures, decreases in annual mean rainfall and relative humidity, and small changes in annual mean wind-speed. Increases in the area extent and frequency of droughts are likely in south-eastern Australia (Hennessy et al., 2008).

Changes in future fire weather risk depend on projected changes in temperature, humidity, rainfall and wind. A modelling study conducted by the Bushfire CRC, the Bureau of Meteorology and CSIRO (Lucas et al. 2007) found that the simulated annual-average number of days with 'Extreme' fire danger increases by 5-25% by 2020 relative to 1990, for a low rate of global warming. For a high rate of global warming, the number of 'Extreme' days increases by 15-65% by 2020. By 2050, the number of 'Extreme' days increases by 10-50% for low global warming and by 100-300% for high global warming.

'Catastrophic' fire-weather was defined as having an FFDI of more than 100 (Lucas et al., 2007). This occurred on 16 Feb 1983 (Ash Wednesday), 18 Jan 2003 (Canberra fire) and 7 Feb 2009 (Black Saturday). Only 12 of the 26 sites analysed in south-eastern Australia have recorded 'Catastrophic' fire-weather days since 1973. By 2020 for high global warming, 'Catastrophic' fire-weather days are predicted to occur at 20 sites, 10 of which have return periods (average time between events of the same magnitude) of around 16 years or less. By 2050 for high global warming, 'Catastrophic' days occur at 22 sites, 19 of which have return periods of around 8 years or less, while 7 sites have return periods of 3 years or less (Lucas et al., 2007).

The implications for fire behaviour will be complex, since more frequent fires will affect ecosystem dynamics and fuel load. Increased fire frequency may result in more frequent less intense fires in a particular location, but may also increase the area burned in a given region. How the landscape and fuels respond to climate change depends on changes in growing conditions (rainfall, temperature), and interactions with fire regimes (i.e. the pattern of recurrence of fires across the landscape; Gill 1975, Bradstock et al. 2002) and land management practices. On the one hand, elevated carbon dioxide levels may enhance vegetation production and thereby increase fuel loads (Booth et al. 2008). On the other hand, drought may decrease long-term vegetation production (and fuels) and may decrease fuel moisture (thereby increasing potential rates of spread). The outcomes of these interacting processes on fire regimes will depend on whether factors act synergistically or antagonistically, are therefore highly uncertain, and require much further research (Williams et al. Forthcoming).

McAneney (2005) reviewed the cost of bushfires in Australia and discussed the risk in the light of past experience. Over the last century, the loss of residential homes from bushfires averaged 83 homes per year, equivalent to about $33.5 million per year for house and contents at 2005 values. However, the year-to-year variance about this mean figure is large ranging from no homes lost in 40% of years to 2500 buildings lost in the Ash Wednesday bushfires (1983), which also killed 75 people. McAneney (2005) estimated a 1-in-100 year event would equate to a likely loss of $0.7 billion and a 1-in-250 year event to a loss of around $1.1 billion, based on house losses (estimated at $440,000 per home including contents at 2005 values). The final toll of the 2009 Bushfires has yet to be calculated but, with about 1800 homes lost, the cost is likely to be greater than the 1-in-100 year event envisaged by McAneney (2005). However, under the changing conditions described by Lucas et al. (2007) past experience may no longer be a reliable indicator of future risk.

2. Preparation and planning to reduce future bushfire threats and risks

(i) Fire danger

The potential for a bushfire to start, to spread across the landscape and do damage defines the danger posed by a bushfire as a result of the combination of fuel and weather conditions. In Australia, the term fire danger also indicates how difficult a fire will be to suppress. Fire danger rating is 'a fire management system that integrates the facets of selected fire danger factors into one or more qualitative or numerical indices of current protection needs' (Chandler et al. 1983). A variety of fire danger ratings are used around the world and most operational fire danger rating systems are based upon the principle that fire danger is determined by wind speed, fuel moisture content, and fuel availability.

There are two fire danger rating systems in use in eastern Australia, one for forest country (the Forest Fire Danger Index (FFDI)) and one for grassland and pastoral areas (the Grassland Fire Danger Index (GFDI)). Two systems are required because forest and grassland fuels have different burning characteristics. For example, forest fuels will burn when grasslands are green and cannot burn, and thus present different levels of danger under the same conditions. In other types of fuels, such as heaths, shrubs or hummock grasses, different danger rating systems could be developed.

The two fire danger rating systems in Australia were developed by A.G. McArthur in the mid-1960s (McArthur 1966, 1967) and have been adopted by all states and territories (except WA in the case of the FFDI) for setting preparedness levels of suppression resources and for declaring days of 'Total Fire Ban'. Each system is represented by an index which is subdivided into rating classes: 'Low' (1-2.5 grass, 1-5 forest), 'Moderate' (2.5-7.5 grass, 5-12 forest), 'High' (7.5-20 grass, 12-24 forest), Very High (20-50 grass, 24-50 forest) and 'Extreme' (50+ grass and forest). These represent the rating of the difficulty of suppression of a well-developed fire in each fuel type.

At a fire danger of 'Low', fires either will not burn or spread so slowly that they are very easy to extinguish. At a fire danger of 'Extreme' fires start very easily from sources which, under milder conditions, normally do not start fires, (e.g. from the hot molten metal produced when powerlines clash together or from the incandescent carbon particles produced by faulty engine exhausts) and spread so rapidly and fiercely that they are virtually impossible to extinguish unless they are attacked within a few minutes of starting (Luke and McArthur 1978).

The factors used to determine fire danger in each fuel type differ slightly, primarily in the treatment of long term moisture. In the GFDI these are degree of grassland curing, air temperature, relative humidity and wind speed. Degree of grassland curing is an estimate of the degree to which the grassland has died off after flowering and setting seed, and thus whether it retains moisture from live cells or is influenced by atmospheric conditions; air temperature and relative humidity provide an estimate of the amount of moisture held within the dead components of the grass. Effects of rainfall are not included, as rainfall events once grasses have cured have a relatively short-lived (1-3 hours) effect.

In the FFDI the factors included are: a measure of the soil dryness (seasonal rainfall deficit), the amount of last rainfall, and the time since last rainfall which are used to determine the percentage of fine litter fuel on the forest floor available for combustion known as the Drought Factor, the air temperature and relative humidity (used to determine the moisture content of the fine fuel) and wind speed. In both meters, the influence of all factors is combined to provide an estimate of fire danger. Not all factors need to be present for fire danger to be High or greater. For example, fire danger may be High with high air temperature and low relative humidity, but little wind. Fuels will be extremely dry and fires may ignite very easily and will not spread very fast, but still be difficult to put out. Conversely when winds are high but fuels are not very dry the fire danger will be High and fires, although difficult to ignite, will still spread and be difficult to suppress. When high air temperature, low relative humidity and high wind speeds coincide, the fire danger will be Extreme.

When first introduced, both systems were capped at an index value of 100 representing the worst possible conditions. For the grassland fire danger index, this was based in part upon the conditions experienced during the Mangoplah fire in southern NSW in January 1952. For the forest fire danger index, this was based upon the conditions recorded at Melbourne during the 1939 Black Friday fires (Sullivan 2004). In revising the grassland fire spread prediction system in the late 1990s (Cheney and Gould 1995, Cheney et al. 1998), it was recognised that conditions had occurred subsequent to the introduction of the meter in 1966 that exceeded McArthur's 'worst possible' and so the index was made open-ended (CSIRO 1997, Cheney and Sullivan 2008).

McArthur's system has been used by rural fire authorities across Australia for more than 40 years, and his fire danger classes have been found to be satisfactory for providing public warnings, setting preparedness levels, and generally providing a good indication of the difficulty of fire suppression over a wide range of conditions (Cheney et al 1990). The amount of fuel present affects fire suppression difficulty; if there is no fuel there is no fire danger at that point in the landscape. However, it is difficult to include fuel load in a fire danger rating system designed to be applied at a regional level. Thus, for general forecasts it is necessary to assume a standard fuel condition. In exceptional circumstances – where fuels are absent or heavily eaten-out across the whole region – sensible adjustments can be made by local fire authorities in setting preparedness levels and providing public warnings on the level of fire danger.

Similarly, difficulty of fire suppression depends on the resources available. For example, one person may find it extremely difficult to suppress a fire under conditions of moderate fire danger, even in sparse fuels. In regions where suppression resources are limited, fire authorities may need to provide public warnings and declare total bans on the lighting of fires at lower values of the fire danger index than are used in areas with higher levels of suppression resources.

The purpose of the McArthur Grassland and Forest Fire Danger Indices (GFDI and FFDI) is to provide a forecast of the likely danger posed by bushfire in standard fuels given a prediction of the weather. These meters required a number of simplifying assumptions to be made in order to be generally applicable for use across the country. One of these was the characteristics of the 'standard' fuel, while another involved the ability of a fire brigade to engage and suppress a fire. To CSIRO's knowledge, to date no fire authority has raised concerns about the use or application of the fire danger meters. Indeed, fire authorities have utilised particular values of the fire danger index to set suppression levels and to guide planning (Luke and McArthur 1978). The predictions of fire danger of February 7 being the worst since Ash Wednesday in 1983 using the FFDI illustrates the capability of such a system to enable suppression preparedness and planning.

Various revisions have been made to the prediction of fire behaviour (Cheney et al. 1998, Gould et al. 2007a,b). However, by preserving the method of determining fire danger, continuity with historical data is provided that enables fire authorities to benchmark response levels and to compare fire weather occurrences. Climate change will affect the weather conditions that drive fuel moisture content and fuel availability (e.g. changes in number of rainy days, number of days with temperature about 40°C) and therefore also change the climatologies of fuel moisture, fuel availability, and FFDI. How particular fire danger rating systems respond to climate change depends on their sensitivities to weather conditions (Matthews 2009).

Climate change may affect distribution of wind speed, but use of wind in the FFDI calculation is not affected. Fuel moisture is calculated using a simple "instantaneous" model based on air temperature and relative humidity. The simplicity of the model means that although climate change may alter the frequency with which certain combinations of temperature and relative humidity occur, the validity of the model is not affected (because temperature extremes increase only slightly, and relative humidity cannot go below 0). Fuel availability is calculated from the amount and time since the most recent rain event. In the FFDI, drying occurs at a constant rate, irrespective of weather conditions. This simple drying assumption, which was a limitation under past conditions, may become even more important under future climatic conditions.

If modifications are made to the drying assumption, this will not affect determination of FFDI at the upper end of the fire danger scale (i.e. High to Extreme) when the drought factor (DF) is at its maximum, but rather at the lower end when fire danger is Low to High. It is at this end of the fire danger scale that fire and land management authorities are able to conduct fuel management practises, such as hazard reduction burning. Having a better understanding of the changes in FDI following rainfall events under changed future climate conditions will improve the safety, effectiveness, and efficiency of such fuel management tasks.

There is some scope to assess current levels of community understanding of the fire indices and how the community uses this information in preparation planning and bushfire response decision making.

(ii) Fire behaviour

Fire behaviour is a collective descriptive term for a number of aspects of a bushfire. These include the rate of spread of the fire (i.e. the speed of the fire in the direction of the wind), the fireline intensity (i.e. the rate of energy release per unit length of fireline), flame height, angle and length, and spotting distance (the maximum distance firebrands will be cast by the fire and spot fires initiated).

The climate change modelling presented in Section 1 shows that in south-eastern Australia the number of days of 'Extreme' fire danger is likely to increase in the coming years. However, the conditions that affect relative fire danger do not always affect the speed of a fire in the same way.

Fire danger and difficulty of suppression are related exponentially to wind speed. That is, as wind speed increases, the difficulty of putting out a fire rises at an ever-increasing rate. In both grassland and forest fuels, the rate of forward spread of a bushfire (that is, the speed of the fire in the direction of the prevailing wind) has a near linear relationship to wind speed. Thus, while wind speed is an important factor in predicting both fire spread and fire danger, fire spread cannot be directly linked to a fire danger index.

The fireline intensity of a bushfire is the product of the rate of spread of the fire, the amount of fuel consumed in the fire, and the heat yield (or energy available) of the fuel. The amount of fuel that is consumed in the fire is also a function of the intensity of the fire. A low intensity forest fire will burn only that fuel on the ground (i.e. surface fuel). As the intensity increases, the fire will consume other strata of fuel (see Figure 8), increasing the amount of fuel consumed and thus the intensity. An extremely intense forest fire may consume all fuel strata within the forest including the canopy.

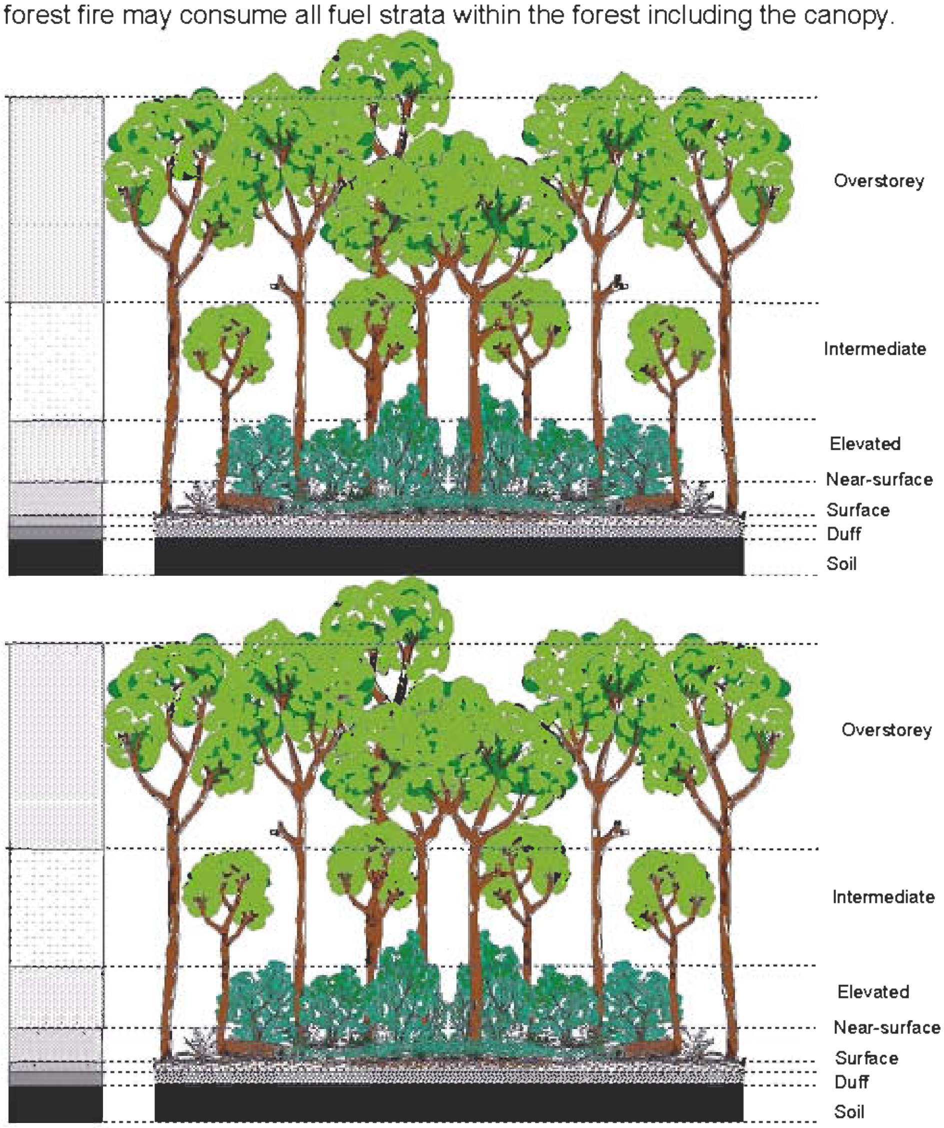

Figure 8: Schematic of the six strata of forest fuel (Source: Gould et al. 2007).

Recent work on determining the behaviour of bushfires in dry eucalypt forests under summer conditions (Gould et al. 2007) found that the speed of a bushfire in these fuels is not only dependent upon the fine surface fuel (as the McArthur system found) but also the structure of the forest understorey. That is, the presence, coverage and height of the near-surface fuel layers. Other layers, such as elevated and intermediate layers, once involved in combustion, contribute to the height of the flames (increasing the difficulty of suppression for a given fire intensity) and provide pathways for the fire to involve the canopy, which may lead to crown fire (see Figure 9). Australian forest types cannot support active crown fire spread without a suitably intense surface fire to provide the energy and mechanisms for fire to reach the often sparse overstorey fuels. It is the bark of the overstorey and intermediate species that provides the fuel for firebrands, which lead to spotting (Ellis 2000).

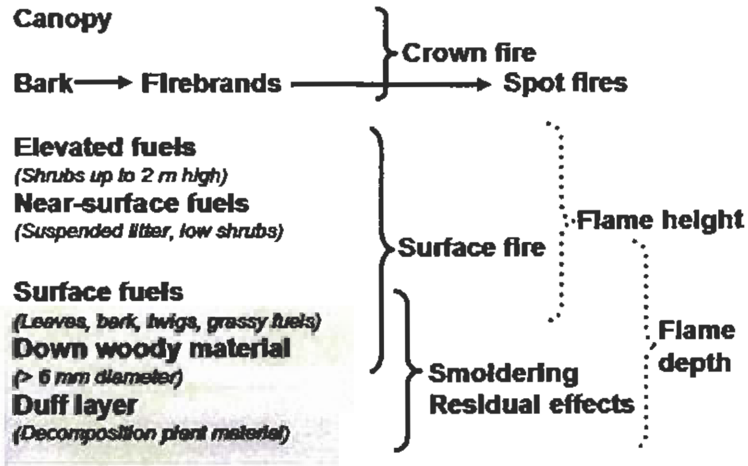

Figure 9: Fuel strata and their relationship with the combustion environment of a bushfire (Source: Gould and Sullivan 2004).

While the impact of changed climate is likely to be an increase in the frequency of extreme fire danger days, the impact of climate change on the structure of the forest and thus the behaviour of bushfires is not known. Changes in species composition and thus structure are likely under sustained changed climate, but the rate of change and the type of change is unknown. Improved modelling of the change in weather variables under changed climate, particularly wind speed, is also critical to predicting the likely change in expected bushfire behaviour under future climate.

(iii) Fuel hazard reduction burning

There are a complex set of interrelating issues surrounding fire management options and their effectiveness at the whole of landscape scale that require consideration in assessing the efficacy of fuel hazard reduction burning. These have been separated into a number of key themes outlined below.

Fuel hazard

Fuel hazard is an estimate of that part of fire danger that is due to the vegetation available for burning (i.e. fuel) (Gould and Sullivan 2004). It is the product of vegetation type, condition, moisture content and structure of the vegetation. It does not have components related to topography (slope and aspect) or wind (speed or direction). Essentially it is the relative flammability of the available vegetation and thus the fuel.

Of the three components that combine to determine fire behaviour (fuel, topography and weather), fuel is the only one that can be modified by people to moderate the behaviour of bushfires (McArthur 1962). Reducing the fuel hazard will reduce the overall danger posed by bushfires and increase the potential that a fire may be stopped through natural or artificial means (Cheney 1996).

Fuel hazard reduction can be undertaken in a number ways, from mechanical removal of fuel through slashing and harvesting, application of chemical treatments (flame retardant, herbicide, etc) or application of fire under suitable predefined (i.e. prescribed) environmental conditions. Prescribed burning is the most cost effective way of reducing fuel hazard at landscape scales (Rawson *et al*. 1985). Hazard-reduction burning is probably the most widespread form of prescribed burning that is deployed on both public and private land in Australia(Gould et al. 2007, Cheney and Sullivan 2008,Dyer et al. 2001)

Most hazard reduction burning conducted in Australia aims to keep the amount of fine surface fuels (fuels less than 6 millimetres in diameter) within the range of 8-15 tonnes per hectare (McArthur 1962; Raison *et al*. 1983; Gill *et al*. 1987; Cheney 1996). Hazard reduction burning also reduces the height, mass and flammability of elevated fine fuels such as shrubs and suspended dead material and is the only practical way of reducing the fibrous bark on trees, the prime source of firebrands that cause spotting (McCaw et al. 2008).

Hazard reduction burning is not intended to stop wildfires, but it does reduce the intensity and the spread of unplanned fires, within the area treated by prescribed fire, by reducing:

- the rate of fire growth from its ignition point;
- flame height and rate of spread;
- the spotting potential by reducing the number of firebrands and the distance they are carried downwind; and
- the intensity of the fire.

As a consequence, hazard reduction burning lowers the risk of crown fires developing in medium to tall forests, will limit the rate of spread and potential impact of wildfires, and makes fire suppression actions safer, more effective and thus more efficient (Luke and McArthur 1978).

The degree of risk reduction will depend on fire weather. During days of extreme fire danger, bushfires will be virtually uncontrollable even if fuels are minimal. However, the number of days each year during which fires will be controllable is many times greater for lighter fuels than for heavier fuels. Thus, there will be more opportunity to suppress fires ignited in summer, and to ensure that they are extinguished before weather conditions worsen. Where fuel loads are very heavy fuel reduction burning requires great care in order to avoid very intense fires, which will pose a hazard to suppression crews and which will have a higher probability of escape. A heavy fuel load is one of the factors associated with the development of characteristics of extreme fire behaviour, which include fast rates of fire spread, long flames and crown fires, fire whirls and excessive spotting.

Research by CSIRO and the Department of Conservation and Environment Western Australia (McCaw *et al*. 2003, Gould et al. 2007a,b) based on fire behaviour experiments in south-west Western Australia and modelling has confirmed that the potential intensity and rate of spread of fires in open eucalypt forests is directly related to the time since last fire. The intensity and difficulty of suppression of fires will continue to increase for at least 15 years after fire because of changes that take place in the structure of surface, near-surface and elevated fuel strata. The amount of most eucalypt fuels will increase rapidly during the first five to eight years after fire and then continue to increase slowly for a further ten years (McCaw *et al*. 2003). In forests dominated by trees with fibrous bark the spotting potential and difficulty of suppression may continue to increase for considerably longer periods after fire as bark continues to accumulate on trees.

The length of time fuel hazard reduction remains effective in assisting suppression of unplanned fires depends upon the number and type of fuel layers involved, and time since fire, as governed by the rate of accumulation of these fuels and the time that it takes for the key layers to build up to their full potential for the site. This ‘effectiveness time’ may be relatively short (less than 1 year) for fuels with a simple structure, such as annual grasses, or it may be many years in more complex fuel types such as tall forests with complex understoreys (Table 1).

Table 1. Period over which fuel reduction burning will assist suppression activities, and the main factors that contribute to difficulty of suppression.

Vegetation type	Persistence of effect on fire behaviour (years)	Factors contributing to difficulty of suppression
Annual grass[2]	1	
Tussock grassland	5	Development of persistent tussock fuel
Tall shrubland[3]	10-15	Height of shrubs, accumulation of dead material (rate of spread, flame height)
Forest, short shrubs, gum bark[4]	10-15	Surface fuel, near-surface fuels structure (rate of spread, flame height)
Forest, tall shrubs, stringybark[3]	15+	Near-surface fuel, shrub height and senescence, bark accumulation (rate of spread, flame height, spotting potential)

If low hazard fuels are maintained adjacent to communities, it is likely that fires will burn out more quickly and residual radiant heat and smoke levels will be less. This means that, following the passage of the fire-front, conditions for residents wishing to extinguish ignitions on structures or to escape from a burning house will be less hazardous. The extent to which houses can survive fires is influenced by many factors including their resistance to ignition by firebrands and the availability of all fuels on the property, including garden fuels, flammable fences and other structures (Ellis and Sullivan 2004).

The 'effectiveness time' or persistence effect of hazard reduction burning, especially the upper bounds of 10-15 years in forests, may be affected by the impacts of climate change. That is, with changes to climatic conditions understorey vegetation species may change and thus may change fuel structure; with declining moisture, rates of fuel accumulation may decline (Williams et al. 2009 forthcoming), potentially lengthening the effectiveness time. Similarly, increased occurrence of days of higher fire danger may reduce overall effectiveness time. Thus, there is a high degree of uncertainty with respect to climate change impacts on this component of fire management and further research is required.

Risk Management

The risk posed by bushfires to assets (communities, biodiversity, infrastructure, etc) can be moderated by hazard reduction burning. However, the level of burning depends on perceptions of acceptable residual risk and acceptable costs (economic, ecological and social). This residual risk will be moderated to some extent by additional actions (such as increased available suppression resources, better community, infrastructure and housing protection, and improved planning and communications).

Prescribed burning is, and will continue to be, an important tool for the management of fire regimes in Australian landscapes in the future. Following the 2003 fires in southern Australia, both the COAG and Esplin Reports (Ellis et al. 2004; Esplin et al. 2003) recommended an increase in the level of prescribed burning in landscapes as part of a general approach to improved fire management. One recent report on fire management on public land in Victoria (Environment and Natural Resources Committee 2008) has recommended (Finding 7.2; p 244) that the level of prescribed burning in the Victorian landscape be increased significantly, partly as a way to mitigate the risk climate change poses to the fire regimes.

The effectiveness of hazard reduction burning will be determined by many factors – the scale of the area to be managed, time since fire, percentage of the total area treated, the suitability, effectiveness, coverage and intensity of the treatment, spatial patterning of prescribed fires, the type of landscape, and fire weather. The level of risk reduction per unit of effort is unclear, with no prescriptions that take into account landscape complexity under conditions of severe or extreme fire weather. Moreover, as indicated above, there will always be residual risk associated with the use of prescribed fire. With respect to climate change, the extent to which risk reduction by prescribed fire is maintained under scenarios of increasing fire danger is also uncertain. There have been a few recent quantitative

[2] Cheney and Sullivan (2008)
[3] Project FUSE: Bushfire CRC (research work in progress).
[4] McCaw et al. (2003), Gould et al. (2007), McCaw (2008)

evaluations of the relationship between area burnt by unplanned fire (or other measure of risk reduction) and area treated by prescribed fire under climate change scenarios in south-eastern Australia; one example is Bradstock et al. (2008). However, as far as CSIRO is aware, no such analyses have been undertaken in the forested landscapes of Victoria and overall understanding would benefit from further research in this area.

Application & Understanding across Spatial Scales

In assessing the potential and effectiveness of hazard reduction burning it is important to highlight that at the scale of the experimental plot (hectares) there is a mature understanding of the effects of fuel reduction burning on fire behaviour, and the time over which these effects can influence fire behaviour. However, at landscape scales (10s-1000s of km^2) the extent to which the area burnt by unplanned fire is mitigated by given levels of treatment of the landscape is complex. In their global review of the effectiveness of prescribed burning and its role in mitigating unplanned fire, Fernandes and Bothello (2003) concluded that "The best results of prescribed fire application are likely to be attained in heterogeneous landscapes and in climates where the likelihood of extreme weather conditions is low. Conclusive statements concerning the hazard-reduction potential of prescribed fire are not easily generalised, and will ultimately depend on the overall efficiency of the entire fire management process."

Cary et al. (2009), in a multi-model, multi-continent comparison of the determinants of area burned, in a range of landscapes across the world, found that 'weather and ignition management were consistently more important for explaining variation in area burned than fuel management approach and effort', King et al. (2006) using simulation modelling in south-west Tasmania, indicated that strategic location of units treated by prescribed fire enhanced the reduction in the fire risk (in that case to vegetation species susceptible to fire).

Other impacts of prescribed burning

Prescribed burning has impacts on numerous values in landscapes, for example biodiversity, water and human health. The interaction between climate change, unplanned fire and prescribed fire on biodiversity values is a developing research area (Williams et al. Forthcoming). Both hazard reduction burning and wildfire can have positive or negative impacts on biodiversity. In some landscapes, there are potential biodiversity costs associated with the intervals between prescribed fires. Water values in some forests may be affected substantially by wildfires, with effects potentially lasting for decades (Kuczera 1987; Lane et al 2006) but are generally little affected by prescribed burning, with exceptions being on highly erodible soils. Smoke from prescribed fires may present health risks, particularly from particles less than 10 microns in diameter (WHO 2003). Air quality issues will continue to be an important part of fire and land management planning.

Hazard Burning Opportunities

Execution of hazard reduction burning is problematic in many areas due to constraints of smoke management, resources and opportunity (i.e. prescription 'window'). In a number of forest types, such the tall, wet montane eucalypt forest types successful execution can limited by the low flammability of surface fuels in general hazard reduction prescription windows, With the expected warmer and drier conditions forecast under changed climate conditions in the future and the subsequent increase in the number of days of extreme fire danger (Lucas et al. 2007), it is expected that current 'windows' for applying prescriptions of hazard reduction burning will change and possibly narrow, meaning less opportunity to conduct safe and effective hazard reduction burns. This will require reassessment of the current operational limits (i.e. work hours, smoke levels, etc) of conducting hazard reduction burning.

(iv) Bushfire suppression and control

Throughout Australia, the initial suppression response to the outbreak of a bushfire is generally the task of the agency with responsibility for the land on which the fire occurs. This response is usually managed at a district level using locally deployed resources. Fires that escape initial suppression attempts will then subsequently attract support from neighbouring districts coordinated at the state level and other agencies with fire fighting resources. In many cases, water-bombing aircraft are not immediately available for early attack on fires and ground crews generally form the primary type of suppression force.

Analysis of data collected from the initial attack of wildfires in a wide range of Australian fuels (Plucinski et al. 2007, 2008) found four main determinants of the success of early fire containment efforts. These were: time to arrival of initial attack response, prevailing weather, level of fuel hazard, and the size of the fire at arrival of initial attack response. With the exception of the prevailing weather, fire management practices can influence all of these factors to improve the probability of success of initial attack.

Time to arrival of initial attack response following detection (i.e. response time) can be minimised by ensuring the deployment of suppression resources is as rapid as possible, that suppression resources are of an appropriate type for accessing the location of the fire, and that suppression resource base locations allow for an optimal coverage of a given area.

The hazard (amount, coverage, and structure) of the burning fuel (McCarthy et al. 1999, Gould et al. 2007b) has a strong influence on initial attack success, as shown in Figure 10, and can be reduced through the application of fuel management practices such as hazard reduction burning (Cheney 1996). Fires burning in areas that have a reduced level of fuel hazard are much more likely to be quickly contained than those that are burning in heavy fuels that are long unburnt.

The size of a fire at arrival of initial attack (i.e. initial fire size) is influenced by suppression response time, fuel hazard, prevailing weather and topography. Initial fire size may be reduced by reducing suppression response time and decreasing the level of fuel hazard. Improved fire detection efficiency will also reduce initial fire size.

In recent years there has been an increased focus on the use of aircraft in the suppression of bushfires. Aircraft have three main advantages over ground suppression resources: speed, access, and observation (Cheney 1996, Plucinski et al. 2007). When ground travel response times are significant or safe access is difficult, aircraft have the ability to reach the fire early in its development and to initiate suppression. In such situations aircraft can be used to hold or slow fire spread to restrict the growth of the active fire perimeter until ground suppression forces arrive. However, once a forest fire has become fully developed, aircraft become less effective at restricting the spread of the fire, primarily due to the increased speed of the fire and the time taken for the aircraft to refill and return to the fire (i.e. turn around time).

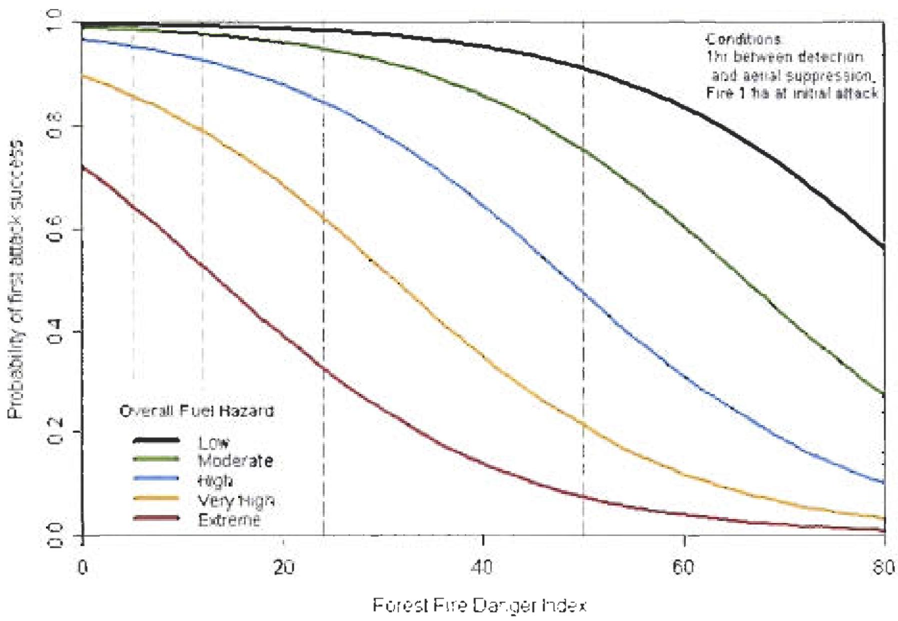

Figure 10: The effect of Forest Fire Danger Index and overall fuel hazard on first attack success (Plucinski et al. 2007).

Aircraft cannot extinguish a bushfire without the support of ground crews (Loane and Gould 1985). While an aircraft can drop water, retardant or chemically-enhanced water (using additives such as surfactants or water enhancing gels), these can only reduce the fire behaviour temporarily; unless directly attacked by supporting ground crews during this period, the fire will eventually burn through, around or over the drop, particularly if the fire is spotting heavily. Aircraft cannot mop-up burning and smouldering fuels which are a primary source of re-ignition (Plucinksi et al. 2007).

Under projected future changed climate conditions, in which the number of days of extreme fire weather is expected to increase for much of south-eastern Australia, improving the success of initial attack will be critical to ensuring large conflagration fires do not develop. Fire management practices, including ignition detection, suppression response using the optimum mix of suppression resources for the conditions and management of fuel hazard, need to be as efficient and as effective as possible to aid initial attack success. A simple adage is that 'small fires are easier to put out than big fires' and this will be even more true given the increased challenges expected from future changes in climate, land use and population demographics.

(v) House loss risk

The McArthur forest fire danger index (FFDI) was originally designed to assist fire-fighters in gauging the degree of safety involved in approaching a fire under given weather conditions. A bushfire hazard index for houses was described by Wilson (1984) and implemented as a House Survival Meter by CSIRO Wilson (1987).

Recent research initiatives (Blanchi et al. forthcoming) have explored the link between historic house losses and the fire weather in which these losses have occurred, as well as other factors including building design, surrounding vegetation and human behaviour. There is potential for an improved house loss risk index to be developed and used to better inform communities of the potential for a fire under given fire weather conditions to cause life and property loss. Accompanied by an integrated education policy this tool could assist individuals and communities to understand:

- the potential worst case weather conditions in their region,
- the capacity to prepare and adapt to their regionally specific weather conditions, and
- the significance of forecast weather conditions in relation to the level to which they are prepared, so that an informed decision can be made to stay and defend or leave well before the fire arrives.

Issues related to buildings and planning are intended to be dealt with in detail in a proposed separate CSIRO report.

(vi) Fire weather projections

Improved fire weather modelling could improve long-term strategic planning for future bushfires. Current modelling has been carried out using a regional model nested in two of CSIRO's global climate models. It would be useful to evaluate the performance of more recent CSIRO global models against other global models developed outside CSIRO. The use of the most reliable models would improve the projections for factors that are critical for bushfires, such as wind speed. Examining daily and annual variability would also assist the assessment of fire weather. The risk of dry lightning (i.e. lightning which occurs without precipitation) is also an important factor affecting fire weather, and this could be analysed in climate change projections. There is potential to enhance the CSIRO-Bureau of Meteorology ACCESS model to include a fire module, linked to a dynamic vegetation model (CABLE). This could provide seasonal and multi-decadal fire weather forecasts.

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Appendix 1 – Contributing Authors

Dr Trevor Booth, Theme Leader in CSIRO's Climate Adaptation National Research Flagship coordinated development of this submission. Contributing scientists with particular expertise relevant to the following sections include:

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1.ii	Mr Kevin Hennessy and Dr Wenju Cai
1.iii	Mr Kevin Hennessy
2.i	Dr Andrew Sullivan and Dr Stuart Matthews
2.ii	Dr Andrew Sullivan
2.iii.	Dr Andrew Sullivan and Dr Dick Williams
2.iv	Dr Andrew Sullivan and Dr Matt Plucinski
2.v	Mr Justin Leonard
2.vi	Mr Kevin Hennessy

Appendix 2 – The science of climate change

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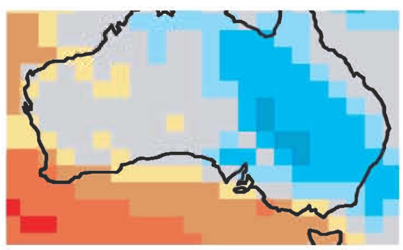

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The science of climate change

Global temperatures are rising

Over the past century the global average surface temperature has risen by 0.74 °C.

The observed increase in average temperatures is widespread around the globe, with rising trends recorded on all continents and in the oceans.

The warming has been fastest over land, and greatest in the upper northern hemisphere. Global ocean temperature rose 0.10 °C between 1961 and 2003, to a depth of 700 m.

In Australia there has been a 0.9 °C warming since 1950.

A shift of just a few degrees in global temperature can cause major changes

Average northern hemisphere temperatures during the second half of the twentieth century were the highest of any 50 year period in the past 1300 years, based on at least 10 temperature reconstructions.

However, this level of warming is not unusual in the Earth's geological history. For millions of years the planet has experienced a series of ice ages and warmer inter-glacial periods, driven mainly by changes in the Earth's orbit.

During the last major ice age, the global average temperature was only 3 to 5 °C cooler than today, and sea levels were up to 120 m lower than present. Around 125,000 years ago our ancestors lived through an inter-glacial period when the polar regions were 3 to 5 °C warmer than the present and sea levels were an estimated 4 to 6 metres higher than the twentieth century. This illustrates that even a few degrees change in global temperatures can create a vastly different environment.

Global sea levels are rising

From 1870 to 2007 the global average sea level rose by close to 20 cm. Sea levels rose at an average of 1.7 mm per year during the 20th century, accelerating to 3.4 mm per year from 1993–2007.

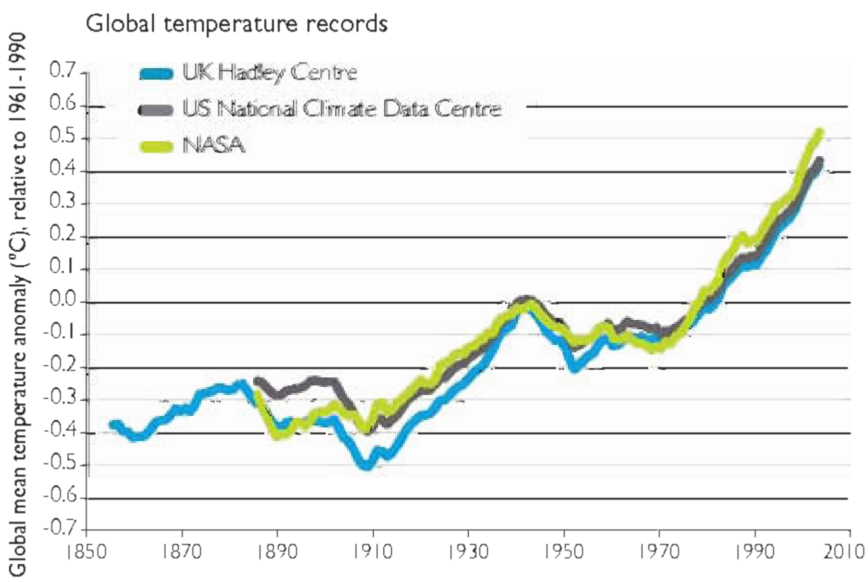
As water warms, it expands in volume. This thermal expansion of the ocean is a major cause of sea-level rise in the 20th century. The other main contributors are the melting of ice-caps and glaciers around the world, and smaller contributions from the Greenland and Antarctic ice sheets.

Extreme weather events and precipitation patterns are changing

Over the last 50 years globally, there have been fewer cold days and nights, and more hot days, hot nights and heatwaves. Heavy rainfall events and extreme sea-level events have increased over most areas.

Since 1900, precipitation has increased significantly over eastern parts of the Americas, northern Europe, parts of Asia and north-western Australia. Reduced precipitation has occurred in central and southern Africa, the Mediterranean and parts of southern Asia. Since 1950, there has been significant drying in south-western and eastern Australia.

These long-term global climate trends are occurring alongside normal weather variations that happen naturally over seasons or decades. The way short-term and long-term variations interact can reduce or worsen the impacts we experience, making it harder to pinpoint all the causes of local temperature changes or specific weather events.



> Figure 1: The three most complete global temperature records available – from the UK Hadley Centre, NASA, and the US National Climate Data Centre – all show a clear upward trend in global average temperatures over the last 150 years (calculated using an 11 year running average).

Greenhouse gases and climate change

Greenhouse gases (GHGs) are a natural part of the atmosphere, trapping and re-radiating heat from the Earth's surface. The natural greenhouse effect is crucial in maintaining a surface temperature that can support life.

The main greenhouse gases are water vapour, carbon dioxide (CO_2), methane, nitrous oxide, halocarbons and tropospheric ozone. Greenhouse gas concentrations are often expressed as a carbon dioxide equivalent (CO_2-e).

Many other natural and human factors also affect the climate. Natural variability such as the El Niño cycle and variations in solar activity can affect the temperature, while large volcanic eruptions can lead to cooling. Changes in land-use can either reduce or increase the amount of heat absorbed by the Earth's surface. Airborne particles (aerosols) have a net cooling effect.

Concentrations of GHGs in the atmosphere have increased since 1750 and now exceed pre-industrial levels

Since the Industrial Revolution, CO_2 concentrations have risen 37%, methane 150% and nitrous oxide 18%. The global increases in CO_2 concentration are due primarily to fossil fuel use and land-use change, while the increases in methane and nitrous oxide are primarily due to agriculture. The CO_2 concentration in 2008 of 383 parts per million (ppm) is much higher than the natural range of 172 to 300 ppm that existed over the last 800,000 years.

There is greater than 90% likelihood that most of the global warming since the mid 20th century is due to increases in greenhouse gas emissions from human activities

The physical and chemical processes involved are well understood and documented, and there is less than 5% likelihood that the observed warming is due to natural causes alone (Fig 2).

Evidence of human influence has been detected in ocean warming, sea-level rise, continental-average temperatures, temperature extremes and wind patterns. This conclusion is consistent with the observed melting of glaciers and ice sheets.

Global average temperature

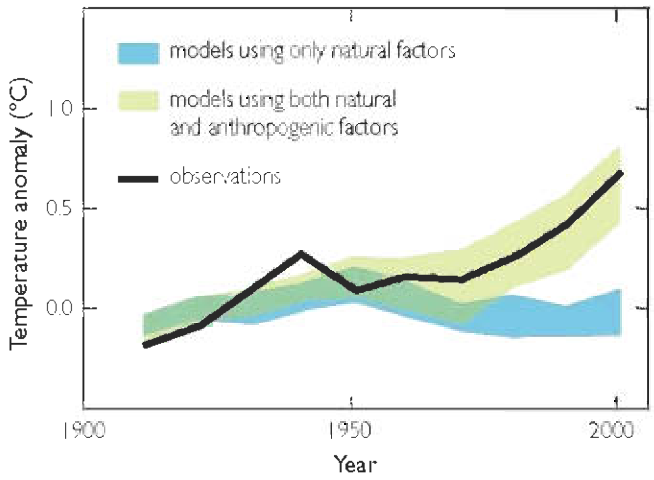


Figure 2: The observed increases in global average temperatures cannot be explained by natural factors alone.

Carbon dioxide affects more than just the climate

About 25% of the CO_2 emitted into the atmosphere is absorbed by the ocean and another 25% is absorbed by the terrestrial biosphere. In water, the CO_2 forms a weak carbonic acid, making the oceans more acidic. Ocean acidification interferes with the formation of shells and coral, and has far reaching implications for the health and productivity of the world's oceans. Higher CO_2 levels can also increase plant growth and productivity but this can be offset by changes in climate such as less rainfall or higher temperatures.

Measuring the climate: then and now

Today, scientists from many nations work together to run a sophisticated global network of weather stations, ocean buoys, tide gauges, satellites and atmospheric sampling stations that constantly measure and record weather, sea levels and greenhouse gas concentrations.

Researchers also analyse older records such as ships' logs, weather reports, tidal records, and archaeological evidence to build up a picture of the Earth's climate over hundreds of years.

To look back beyond this, scientists analyse proxy temperature records such as the annual growth rings of trees and corals, and small fossils in lake sediments. For example, sediment cores can indicate how coastlines have shifted with changes in sea level. Bubbles of air trapped deep in polar ice can reveal temperatures and atmospheric concentrations of greenhouse gases up to 800,000 years ago

The amount of future climate change depends on the level of global greenhouse gas emissions

Research groups around the world have independently developed climate models, which each have their own strengths and weaknesses. After careful testing, these models are used to project likely future changes in the climate based on various emission scenarios.

Concentrations of greenhouse gases are continuing to rise, and some GHGs have long lifetimes in the atmosphere. Due to this inertia, the climate changes projected for 2030 are unavoidable.

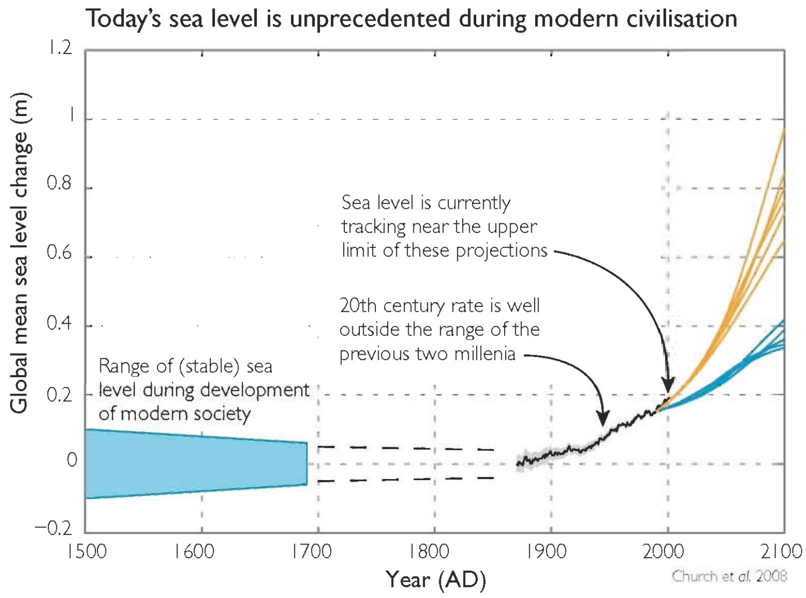
The current rate of GHG emissions is above the highest scenario developed by the Intergovernmental Panel on Climate Change (IPCC). The scenarios used in the IPCC's most recent report no longer adequately describe emerging emission trends over the next few decades. New estimates accounting for recent emission trends indicate that by 2030 CO_2 emissions may be 17 to 52% higher than estimated by the IPCC. This would likely result in a global warming of 0.8 to 1.5 °C by 2030.

Continued greenhouse gas emissions at or above current rates will cause further warming and induce many changes in the global climate system during the 21st century. There is greater than 90% likelihood that these changes will be larger than those already seen during the last century.

There is greater than 90% likelihood that heat waves and heavy rain events will continue to become more frequent around the world. Sea-ice and snow cover are projected to shrink. There is greater than 90% likelihood that rainfall will increase in high latitudes and greater than 66% likelihood that rainfall will decrease in most sub-tropical and temperate land areas. There is greater than 66% likelihood that the area affected by droughts will increase and there is greater than 66% likelihood that that tropical cyclones will become more intense.

By 2050, different trends in emissions have a significant influence on climate outcomes. If significant mitigation efforts start in 2010, leading to emissions peaking in 2020 and CO_2 equivalent concentrations stabilising around 600 ppm after 2060, scientists project a warming of 1.1 to 2.2 °C by 2100. The chance of avoiding a warming of 2 °C would be around 90%.

However, if global emissions continue to climb so that CO_2 equivalent concentrations exceed 970 ppm by 2100, then temperatures are projected to increase by 2.2 to 4.7 °C by 2100, and there would be little chance of avoiding a 2 °C warming.



> Figure 3: Global sea level was stable for at least two thousand years before starting to rise in the 19th century and the rate of rise has increased since then. Currently sea level is tracking near the top of the IPCC projections. The orange lines show the high (95%) values for six IPCC SRES scenarios. The blue lines show the low (5%) values for the same six scenarios.

Sea level is projected to rise further by the end of this century

Ongoing warming of the oceans and melting of ice are expected to lead to continued sea-level rise of at least 18 to 79 cm this century. Due to limited understanding of how ice-sheets in Greenland and the Antarctic will respond to rising temperatures, a rise of more than 79 cm by 2100 cannot be ruled out. Although our understanding of how ice sheets melt and decay is improving, there is currently no scientific consensus on a best estimate of their contribution to sea-level rise by 2100.



Projections for Australia's climate

Australian average temperatures are projected to rise by 0.6 to 1.5 °C by 2030 and by 1 to 5 °C by 2070

The warming projected for Australia in 2070 is 1.0 to 2.5 °C for a low emission scenario (similar to a 500 ppm CO_2 equivalent path) and 2.2 to 5.0 °C for a high emission scenario (similar to the world's current path).

Warming is projected to be lower near the coast and in Tasmania and higher in central and north-western Australia. These changes will be felt through an increase in the number of hot days. In Canberra, for example, the present annual average of five days over 35 °C may rise to seven to 10 days by 2030 and eight to 26 days by 2070.

Average annual rainfall is likely to decrease over much of Australia

Projectons indicate by 2030, southern Australia may receive up to 10% less rainfall while northern areas see changes of -10 to +5%. By 2050, southern areas may get 0 to 20% less rainfall, with changes of -20 to +10% in the north. Water security problems are projected to intensify by 2030 in southern and eastern Australia as a result of reduced rainfall and higher evaporation.

The frequency and extent of droughts is projected to increase over most of southern Australia. However, it is difficult to determine with certainty how much of the drying of the past decade is due to human activities.

The pattern of severe weather events is expected to change

The effects of climate change will be superimposed on natural climate variability, leading to changes in the frequency and intensity of extreme weather events.

- There is greater than 90% likelihood that xtreme fire weather is will occur more often in southern Australia, with longer fire seasons.
- Days with heavy rainfall are projected to become more intense over most areas in summer and autumn and in northern areas in winter and spring.
- Tropical cyclone days are projected to increase in the north-east but decrease in the north-west, with the strongest cyclones becoming more intense.
- The number of days with large hail is projected to increase along the east coast from Fraser Island to Tasmania and decrease along the southern coast of Australia.

Coastal settlements and infrastructure

By 2050, Australia's growing coastal towns and cities will face heightened risks from sea-level rise and more frequent severe storms and flooding. Global climate models indicate that mean sea-level rise on the east coast of Australia may be greater than the global mean sea-level rise. In low-lying areas, a mean sea-level increase of 18 to 79 cm or more could lead to coastal inundation tens or even hundreds of metres inland depending on local topography.

Risks to major infrastructure are expected to increase, including: failure of flood protection, urban drainage and sewerage; increased storm and fire damage; and power-outages during heat waves.

The natural environment

Significant loss of biodiversity is projected to occur as early as 2020 in some ecologically rich sites. For example, rising sea temperatures are almost certain to increase the frequency and intensity of mass coral bleaching on the Great Barrier Reef. Other sites at risk include the Queensland wet tropics, Kakadu wetlands, south-west Australia, sub-Antarctic islands and the Australian alps.

Primary industries

Production from primary industries is projected to decline by 2030 over much of southern and eastern Australia due to increased drought, reduced water resources and higher temperatures. Changes in the distribution and abundance of commercial fish species may create new opportunities in some coastal regions, but overall projected changes in climate pose some very significant risks to the fishing industry.

Human health

One of the major health impacts is likely to be an increase in heat-related deaths. Without preventative action, the number of heat-related deaths in people aged over 65 could rise from 1115 per year at present in the major capital cities, to between 4300 and 6300 per year by 2050. Some mosquito-borne diseases may move south, e.g. dengue fever.

Science based solutions

A comprehensive response to climate change requires three broad areas of action: mitigation, to reduce greenhouse gas emissions; adaptation, to prepare for impacts that are now unavoidable; and continued research to better understand the earth's climate systems.

Reducing greenhouse gas emissions

Many of the impacts of climate change can be reduced, delayed or avoided by reducing greenhouse gas emissions. One of the key messages from the science is that mitigation efforts over the next few decades will have a large influence on whether GHG concentrations can be stabilised at a level low enough to reduce the risk of more serious climate change impacts.

Cutting Australia's GHG emissions is a major national undertaking that involves households, companies, communities and governments. The goal of CSIRO's Energy Transformed National Research Flagship is to develop stationary and transport technologies to halve GHG emissions, double the efficiency of the nation's new energy generation, supply and use, and to position Australia for a future hydrogen economy.

Preparing for the impacts of climate change

Australians have a long history of coping with the vagaries of a highly variable climate, and the nation enjoys a high standard of living, so we have the capacity to adapt and prepare for some of the impacts of climate change. Early studies indicate that for Australian agriculture, adaptation measures could reduce the impacts of climate change on productivity by almost 50 per cent, and substantially reduce the economic cost to regional communities.

Potential actions to adapt to life in a changing climate include: choosing development sites that will be less affected by extreme weather events; improving building design; reducing water use and developing new water sources; switching to more drought-tolerant crops; improving the resilience of ecosystems threatened by climate change; and assisting our neighbours in the Asia-Pacific region.

Climate change research is improving our knowledge and addressing uncertainties

Our present scientific understanding of climate change, although incomplete, is sufficiently robust to inform decision making and action.

However, the fact that many key aspects of the science of climate change are now well understood and agreed has not eliminated all uncertainties. Remaining uncertainties arise from three main sources:

- Current limits and gaps in our knowledge about physical climate processes, for example: how much influence are aerosols having on the climate system?
- The complexity of modelling the global climate system, for example: how can we more accurately simulate future rainfall patterns?
- The inherent difficulty of predicting human behaviour, for example: how fast will developing economies grow and how will this affect their net emissions of GHGs and aerosols?

Furthermore, the risk posed by positive feedback loops is poorly understood. Potentially significant feedbacks that could accelerate climate change and its impacts include: the release of GHGs from melting permafrost; changes in how much carbon dioxide is absorbed by the natural environment as temperatures rise; and increased heat absorbed by the oceans as sea ice retreats.

For further information

Further information and resources, including a fully-referenced version of this brochure, are available at www.csiro.au/climatechange

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Cover: The research vessel *Southern Surveyor* is used to deploy yellow Argo Floats that monitor ocean temperatures, providing vital data about climate change; bore tank in drought; climate model – © CSIRO • Gold Coast erosion – © Bruce Miller. **Page 4:** dam; cracked earth – © CSIRO • a stream of melt water cascading off the Arctic ice sheet – © Roger Braithwaite. **Page 5:** plume from a tall chimney stack; wind turbine; children on the beach – © CSIRO.

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