Australian Government

Department of Climate Change

Department of the Environment, Water, Heritage and the Arts

IMPLICATIONS OF CLIMATE CHANGE FOR AUSTRALIA'S WORLD HERITAGE PROPERTIES: A PRELIMINARY ASSESSMENT

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A report to the
DEPARTMENT OF CLIMATE CHANGE and
the DEPARTMENT OF THE ENVIRONMENT, WATER, HERITAGE AND THE ARTS.

Prepared by
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The views and opinions expressed in this publication are those of the authors and do not necessarily reflect those of the Australian Government or the Minister for Climate Change and Water and the Minister for the Environment, Heritage and the Arts.

Note on the names of departments referenced in this report

Name changes to the Australian Government's environment department have occurred over the past several years. This report refers to:

- The Department of the Environment and Heritage (DEH)—former name
- The Department of the Environment, Water, Heritage and the Arts (DEWHA)—current name
- The Department of Climate Change—current name (part of which was formerly the Australian Greenhouse Office in DEH)

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Australian Government
Department of Climate Change
Department of the Environment, Water, Heritage and the Arts

PREFACE BY THE AUSTRALIAN GOVERNMENT

World Heritage properties are important to all people and have a universal value that transcends national boundaries. Australia's 17 World Heritage properties include the largest World Heritage property, the Great Barrier Reef, extensive natural and Indigenous places like Kakadu National Park, isolated marine and terrestrial areas such as Macquarie Island, and Sydney Opera House, an architectural masterpiece. Climate changes such as sea level rise, reduced rainfall and higher temperatures are expected to threaten the resilience of our World Heritage properties, exacerbating issues such as habitat loss and degradation, spread of invasive species and changing fire regimes.

Committed to protecting the values of Australia's World Heritage properties, in 2006 the Australian Government asked the Australian National University to assess the exposure, potential impacts, vulnerability and adaptive capacity of our World Heritage properties to climate change and to identify major knowledge gaps. This resulting report will inform management plans and government policy on World Heritage and climate change adaptation into the future.

Some of our World Heritage properties have already embarked on far-sighted initiatives to manage the effects of climate change. For example, the Great Barrier Reef Marine Park Authority has completed a detailed vulnerability assessment and is implementing an $8.9 million Climate Change Action Plan, and a $200 million Reef Rescue Plan, funded by the Australian Government.

A range of other Australian Government and intergovernmental studies and initiatives are contributing to our understanding of the risks posed to biodiversity and natural landscapes from climate change. The National Climate Change Adaptation Framework is the basis for government action on adaptation over the next five to seven years, and it includes actions to assist the most vulnerable sectors and regions of the country. $126 million has been provided towards the implementation of the framework, including the establishment of a Climate Change Adaptation Research Facility, which will lead Australia's researchers in generating robust biophysical, social and economic information that decision makers need to manage the risk of climate change.

One of the first countries to ratify the World Heritage Convention in 1974, Australia is committed to helping other countries protect World Heritage. Keen to share our skills and experience on World Heritage and climate change, in 2007 we provided significant input and guidance on the World Heritage Convention's Climate Change Policy. Our election to the World Heritage Committee in 2007 for a four-year term provides further opportunities for collaboration.

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Abbreviations

AAD	Australian Antarctic Division
AGO	Australian Greenhouse Office (now the Department of Climate Change)
BOM	Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCC	Department of Climate Change
DEH	Department of the Environment and Heritage (now the Department of the Environment, Water, Heritage and the Arts)
DEWHA	Department of the Environment, Water, Heritage and the Arts
EAC	East Australian Current
ENSO	El Niño Southern Oscillation
EPBC	Environment Protection and Biodiversity Conservation
GBRMPA	Great Barrier Reef Marine Park Authority
GIS	geographic information systems
IPCC	Intergovernmental Panel on Climate Change
UNESCO	United Nations Educational, Scientific and Cultural Organization

EXECUTIVE SUMMARY

Australia is one of the oldest continents on earth, and is unique in terms of its cultural, geographical and biological diversity. There are currently 17 sites in Australia recognised by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as possessing characteristics *considered to be of outstanding value to humanity*. Because of their global significance, these sites are listed as World Heritage properties. However, Australia's World Heritage properties, and their values, are under threat from global climate change.

The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007) states that '*global warming is unequivocal*' and is due largely to an increase in greenhouse gases, such as carbon dioxide (CO_2), caused by burning fossil fuels. Australia's average surface temperature has increased by about 0.7 °C since 1900 (IPCC 2007). From 1993 to 2003, global mean sea level has been rising at a rate of around 3 mm/yr (Bindoff et al. 2007). Thermal expansion of the oceans and widespread melting of land ice will result in further global sea level rise.

Australia—already the driest inhabited continent on earth—is particularly vulnerable to climate change. Australia is one of the most biologically diverse countries, and is home to more than one million species, many of them endemic. Species endemic to Australia include 85% of our flowering plants, 84% of our mammals, 89% of our temperate in-zone fish and 45% of our birds.

Reduced rainfall, higher sea and land surface temperatures, more severe storm events, ocean acidification, and rising sea levels are expected to impact significantly on Australia's unique World Heritage values, particularly the natural values listed under UNESCO's criterion (x), i.e. those sites that '*contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation*'.

Because Australia's World Heritage sites are isolated from each other and have very different geographical characteristics, the severity of climate change threats is likely to vary across the World Heritage estate. It is likely that, with continued global warming, there will be substantial reductions in the area of rainforests, declines in the abundances of native fauna and flora, expansion of woody vegetation into arid and semi-arid rangelands, and continued coral bleaching. Changes in the abundance and distribution of many species, including the extinction of indigenous plants and animals with limited dispersal capabilities and/or narrow climatic tolerance ranges, are also expected. These impacts are likely because rates of climate change are highly likely to occur faster than the rates of evolutionary adaptation of many plant and animal species. Extreme weather events are likely to result in irreversible damage (i.e. erosion) to geological, geomorphologic and physiogeographic heritage, whose values are embodied in UNESCO's criterion (viii), i.e. '*to be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features*'. Furthermore, the preservation of unique cultural values—including Aboriginal middens, sea cave deposits, archaeological sites, rock art and cave art sites—is highly dependent on the maintenance and protection of their underlying landforms from climate change impacts. Other cultural values, such as architectural heritage, are also likely to be affected by climate change but to a lesser extent, at least in the short term.

Australia's biological diversity is already under stress from human impacts particularly caused by land use change, hydrological change, soil salinisation, invasive species and changes to fire regimes. Climate change is an additional stress. It includes stresses such as higher temperatures, changed water and fire regimes, more extreme weather events, and salt water inundation into freshwater coastal wetlands, including those that are World Heritage listed.

The recent *IPCC Fourth Assessment Report—Impacts, Adaptation and Vulnerability* (IPCC 2007) noted that significant loss of biodiversity is projected to occur by 2020 in some ecologically rich sites—many World Heritage listed—including the Great Barrier Reef and Wet Tropics of Queensland, with other sites at risk including the Kakadu wetlands, south-western Australia, sub-Antarctic islands and alpine areas. It also noted that natural systems have a very limited adaptive capacity, and that habitat loss and fragmentation are very likely to limit species migration in response to shifting climatic zones.

Climate change will modify the natural and cultural values of Australia's World Heritage properties. This in turn may affect their outstanding universal values and may affect their status as World Heritage sites. Put succinctly: '*If a site was inscribed for its glaciers, and the glaciers melt, is it "no glaciers—no World Heritage site?"*' (UNESCO 2006).

The report

Prepared by The Australian National University for the Australian Government Department of Climate Change and Department of the Environment, Water, Heritage and the Arts, the report provides a preliminary assessment of the vulnerability of the World Heritage values of Australia's World Heritage properties to the impacts of climate change.

The report is based on extensive review of the scientific and heritage literature and, where possible and time permitting, consultations with World Heritage property managers and scientists who have conducted work within the properties or provided advice to property managers.

The primary aims of the report are to:

- assess the vulnerability of the World Heritage values of each World Heritage property to climate change impacts
- identify World Heritage values that are highly vulnerable to climate change impacts
- identify major gaps in knowledge about the vulnerability of World Heritage values to climate change impacts.

The report has been prepared within the context of the growing understanding within Australia and internationally of the extent of impacts, both observed and projected, of climate change on human and natural systems. The World Heritage Committee of UNESCO, at its 29th session in 2005, recognised that climate change is already affecting the natural and cultural values of many World Heritage properties, and is likely to affect many more in the years ahead.

In scoping likely climate change impacts, vulnerability and adaptive capacity of the World Heritage values of Australia's World Heritage properties, this report identifies information gaps and provides the basis for further, more detailed, responses by governments, property managers and researchers.

Climate change context

There is now a general consensus that climate change is occurring and the earth is warming. In its Fourth Assessment Report (IPCC 2007), the IPCC found that '*warming of the climate system is unequivocal*' as a result of alteration to the energy balance of the atmosphere through markedly increased levels of greenhouse gas emissions into the atmosphere from human activities since 1750.

Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought regimes. The IPCC report found, for example, that more intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics.

Average surface temperatures across Australia have increased by as much as 0.7 °C since 1910 and 0.6 °C ± 0.2 °C globally since the early 1900s. For the next two decades, a global warming of about 0.2 °C per decade is projected for a range of emissions scenarios. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Bureau of Meteorology (BOM) have investigated future climate change projections for Australia in more detail. Relative to 1990 temperatures, these projections indicate a warming trend across the continent by as much as 1.8 °C by 2030 in some regions and as much as 5 °C by 2070 (CSIRO and BOM 2007).

Australian rainfall patterns are expected to change, with northern Australia likely to receive more rainfall while southern and south-eastern Australia will likely receive less. Water availability and quality, and runoff into streams, are likely to be affected by higher temperatures, increased evaporation rates and lower soil moisture content, and changes in amount and patterns of rainfall. Increased evaporative demand (evaporation and evapotranspiration) associated with higher temperatures are likely to lead to an increase in severe droughts for the majority of Australia's World Heritage properties. However, there is an increased likelihood of more severe storm events and cyclones (CSIRO 2006).

Sea level is expected to increase by 2030 by an average of 17 cm under a continued 'High greenhouse gas emissions' scenario (CSIRO 2006). However, even rises expected under a more moderate scenario would be undesirable for some of Australia's World Heritage properties such as Kakadu National Park and Shark Bay, Western Australia.

Climate change projections for each of Australia's World Heritage properties are summarised in this report.

Potential climate change impacts on World Heritage values

Australia's World Heritage properties and their World Heritage values are diverse, and not all will be affected equally by climate change. Some properties, such as the Great Barrier Reef and the Wet Tropics of Queensland, are highly sensitive, whereas others such as Naracoorte (Australian Fossil Mammal Sites) are likely to be more robust.

Palaeoclimatic studies have revealed that some of Australia's World Heritage properties have undergone periods of considerable change through a series of glacial cycles. These studies provide a clear indication that the World Heritage values of these properties will continue to change in response to 'natural' or non-anthropogenic climate change processes. However, what is uncertain is the responsiveness and inherent adaptive capacity of World Heritage properties and their values to abrupt or more rapid change in climate resulting from anthropogenic (human-induced) effects. There is also uncertainty as to the capacity of managers and property management systems to assist World Heritage properties or specific values to adapt in the face of rapid climate change.

The severity of climate change threats also varies considerably across the World Heritage estate and is often location-specific. The literature of potential climatic impacts on individual values is extremely uneven. Such 'patchiness' inhibits an authoritative overall assessment across the properties.

A summary of some of the key values of each of Australia's World Heritage properties, the major threats to these values from climate change and likely adaptive capacity, are provided in Appendix C to the report.

Impact on ecological values

Those World Heritage properties that have 'outstanding universal value', as assessed against World Heritage criterion (ix)—'*to be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals*'—and criterion (x)—'*to contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation*'—are likely to be the most affected by climate change. However, the impacts of climate change will not necessarily remove the outstanding universal value of a World Heritage property as assessed under these or other criteria.

Impacts on values associated with criteria (ix) and (x) may occur because projected rates of climate change are highly likely to occur faster than rates of evolutionary adaptation in many plant and animal species. Lower rainfall and higher temperatures are also expected to impact significantly on plant and animal species across all World Heritage properties, with substantial contractions in some communities, such as rainforest communities, and declines or distribution changes in some plant and animal species. Bioclimatic modelling has revealed that the bioclimates of some species are likely to vanish with only a moderate increase in temperature (1 °C).

Some future climate change impacts on biodiversity values in World Heritage properties include:

- the loss of freshwater wetland species and the continued expansion of mangrove communities along tidal rivers resulting from rising sea levels
- a predicted lift in the orographic cloud layer, which may lead to the decline or disappearance of most endemic plant and animal species that rely on mountain-associated precipitation from cloud mist
- increases in plant productivity and continued expansion of woody vegetation into arid and semiarid rangelands from increased carbon dioxide (CO_2); however, this may be countered by reduced rainfall
- continued changes in distribution and abundance of plant and animal species on sub-Antarctic islands associated with glacial retreat and other impacts
- rising sea surface temperatures and ocean acidification, which will continue to impact on marine organisms including coral.

Although fire has always been a natural phenomenon of the Australian landscape, changing fire regimes (more intense and frequent) as a result of climate change have emerged as a major threat to biodiversity values.

Impact on geomorphic and aesthetic values

World Heritage values listed under criterion (vii)—'*to contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance*'—and criterion (viii)—'*to be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features*'—are also likely to be affected by climate change, but to a lesser extent in the short term. These include landforms, or significant geomorphic or physiographic features. Impacts of more intense fires—including effects due to heating and soot damage, changes to rates of erosion, and changes to coastal geomorphology from rising sea levels and storm events—are the most common threats to landforms and physiographic features from climate change.

Impact on cultural values

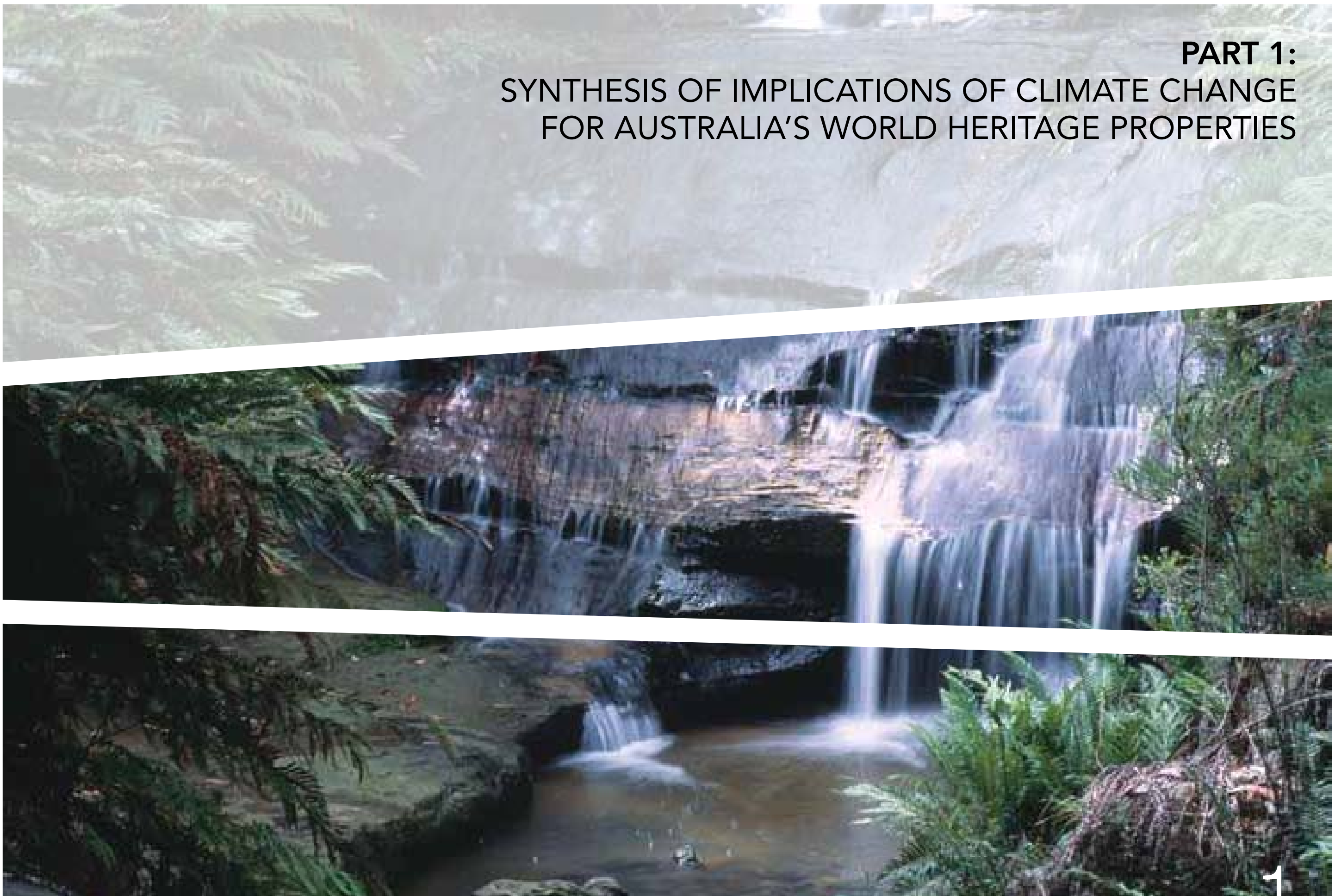
Unlike the natural criteria and respective values, there is little information available on the potential impacts of climate change on cultural values of Australia's World Heritage properties. The literature has concentrated on specific site management issues such as restrictions on access to sites and excavation. Because there is little knowledge or understanding of potential impacts of climate change on cultural values, the extent of vulnerabilities would appear to be worthy of identification and assessment in the context of specific site management issues. However, based on limited information, the potential impacts on cultural values (criteria (i) to (vi)) might include excessive erosion from extreme weather events, changes to vegetation from drought, changes in rainwater pH, and heat and soot from intense fires. In addition, storm-surge and saline intrusion into coastal regions is likely to affect low-lying, coastal cultural values. A table summarising the potential impacts of climate change on Australia's World Heritage properties (Table 3) can be found in Part 1 of the report.

Incorporating climate change into management

The findings in this report raise important issues relating to the management of World Heritage properties, and the development and prioritisation of programs that will ameliorate the impacts from climate change on values with low adaptive capacity. Future work must focus on the development of strategies that will ameliorate the effects of climate change, as well as on the need to identify the extent of vulnerabilities for risk preparedness planning. Furthermore, since Australia's World Heritage sites do not share common management structures or systems, efficiency may be able to be improved by improving communication and networking between all World Heritage properties. The vulnerability of archaeological and other cultural heritage sites—as well as the social, legal and economic costs to the community from lost heritage—requires further identification and assessment.

Climate change cannot be examined in isolation but must be viewed in context with current threats and problems associated with the protection of natural and cultural values. Climate change effects are likely to exacerbate the current problems associated with human-induced changes to the landscape through deforestation, fire, urban expansion, water extraction, tourism development and visitation as well as non-anthropogenic factors such as the spread of exotic pests and diseases. Management strategies could be aimed at facilitating resilience to climate change through the removal or control of other environmental stress factors. Needs identified by the preliminary assessment include:

- climate change management plans for Australia's World Heritage properties, climate change information sharing systems, and communication networks and climate change training for managers
- global climate change models for fine-scale prediction relevant to World Heritage properties, including enhanced data collection with ecological and genetic baseline data and palaeoclimatic data
- fire-related research into ecosystem responses and a national database of species responses
- a further assessment of vulnerability of cultural World Heritage values to climate change
- strategies to avoid habitat fragmentation and enhance ecological connectivity of World Heritage properties in their landscape and ecosystem contexts
- reclamation strategies to provide refuge habitat for threatened species of World Heritage value.



PART 1:

SYNTHESIS OF IMPLICATIONS OF CLIMATE CHANGE FOR AUSTRALIA'S WORLD HERITAGE PROPERTIES

1. INTRODUCTION

There are currently 17 properties within Australia recognised by UNESCO as having outstanding universal value to humankind. Because of their universal significance, these properties are listed as World Heritage sites. The World Heritage Committee of UNESCO, at its 29th session in 2005, recognised that climate change is already affecting the natural and cultural values of many World Heritage sites around the world, and is likely to affect many more in the years ahead (UNESCO 2006). The United Nations Intergovernmental Panel on Climate Change (IPCC) found that climate change is expected to cause significant loss of biodiversity in some ecologically rich sites, including Australia's Great Barrier Reef, Queensland's Wet Tropics, the Northern Territory's Kakadu National Park and Australia's sub-Antarctic islands, which are all World Heritage-listed properties.

The responsiveness and inherent adaptive capacity of Australia's World Heritage properties to abrupt changes in climate resulting from anthropogenic effects is uncertain. There is also uncertainty as to the capacity of property managers and management systems to facilitate the adaptation of World Heritage properties and specific values in the face of both abrupt and gradual climate change.

1.1 Scope of the report

This report provides a preliminary assessment of potential climate change on Australia's World Heritage properties, and the vulnerability and adaptive capacity of the natural and cultural values most likely to be affected significantly by the direct and indirect effects of climate change. Recommendations for future research and actions are also outlined. This report has been prepared by the Fenner School of Environment and Society of the Australian National University, for the Australian Government Department of Climate Change and the Department of the Environment, Water, Heritage and the Arts.

The primary aims of the report are to:

- assess the vulnerability of the World Heritage values of each World Heritage property to climate change impacts
- identify World Heritage values that are highly vulnerable to climate change impacts
- identify major gaps in knowledge of vulnerability of World Heritage properties or values to climate change impacts.

This report is based on an extensive review of the scientific and heritage literature and, where possible and time permitting, consultations with World Heritage property managers and scientists who have conducted work within the properties or provided advice to property managers.

This report draws on a review of literature undertaken largely in 2006–2007, and provides a synopsis of future impacts based on current scientific literature and advice. Where possible, and where supported by evidence contained in the scientific literature or provided by managers or scientists, this report has assessed the likely vulnerability of the natural and cultural values of Australia's World Heritage properties to future climate change. It was not possible to comment on the potential impacts of climate change on all World Heritage values, as there was not sufficient scientific information to support this level of analysis for all values. Where there is a clear gap in information on climate change impacts on particular values, the authors have noted this. Furthermore, the authors of this report have made no attempt to make an independent judgement or assessment on what impacts climate change would have on Australia's World Heritage values.

Structure of the report

Where possible, this report has addressed the likely response of each value for all 17 World Heritage properties to future climate change. Summary information provides an overview of exposure, sensitivity, adaptive capacity, vulnerability and gaps in knowledge for each World Heritage value. A brief one to two-paragraph summary of future climate change impacts is also provided on each property.

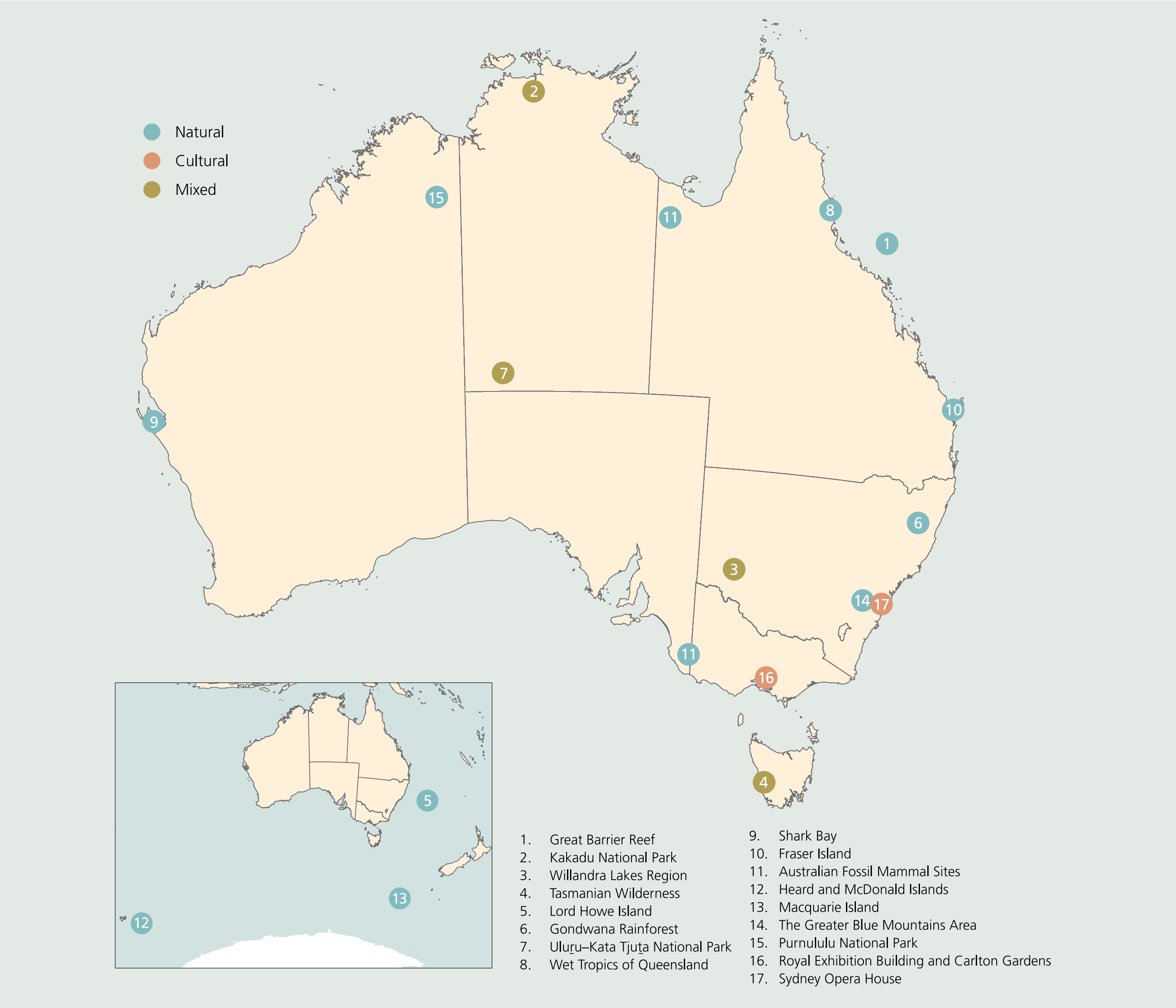
This report is divided in two parts. Part 1 is a synthesis of important implications of climate change for World Heritage properties, followed by recommendations and future directions. Part 2 contains an analysis of the potential impacts of climate change on Australia's World Heritage properties and values. Gaps in knowledge and future directions are outlined for each World Heritage property.

1.2 What is a World Heritage property?

In 1972 UNESCO adopted a convention dealing with the 'Protection of the World Cultural and Natural Heritage'. This convention is UNESCO's mandate to '*encourage the identification, protection and preservation of cultural and natural heritage around the world considered to be of outstanding value to humanity*'.[1] To qualify for World Heritage status, heritage sites proposed for nomination must have values that are 'outstanding as well as universal'.

Australia's World Heritage properties cover regions of extreme climate variability. These range from the Wet Tropics of north Queensland and the savanna country of the Top End, to the sub-Antarctic conditions of Heard and McDonald Islands. The locations of Australia's World Heritage properties are shown in Figure 1.

Figure 1. Location of Australia's World Heritage Properties. (Courtesy of the Department of the Environment, Water, Heritage and the Arts.)



1 <http://whc.unesco.org/en/about>

Cultural and natural heritage are defined in Articles 1 and 2 of the World Heritage Convention. Under Article 1, 'cultural heritage' is considered to comprise:

- *monuments*: architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings, and combinations of features, which are of outstanding universal value from the point of view of history, art or science
- *groups of buildings*: groups of separate or connected buildings which—because of their architecture, their homogeneity or their place in the landscape—are of outstanding universal value from the point of view of history, art or science
- *sites*: works of humans or the combined works of nature and of humans, and areas including archaeological sites that are of outstanding universal value from the historical, aesthetic, ethnological or anthropological points of view.

Under Article 2, 'natural heritage' is defined as:

- *natural features* consisting of physical and biological formations or groups of such formations, which are of outstanding universal value from the aesthetic or scientific point of view
- geological and physiographic formations, and precisely delineated areas, which constitute the *habitat of threatened species of animals and plants of outstanding universal value* from the point of view of science or conservation
- natural sites or precisely delineated *natural areas of outstanding universal value from the point of view of science, conservation or natural beauty* [our emphasis].

Properties nominated for World Heritage status have their values assessed against UNESCO's 10 criteria, explained in the *Operational Guidelines for the Implementation of the World Heritage Convention*.[2]

Examples of UNESCO's criteria to be listed on the basis of natural significance include: '*… outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals*' and '*… outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features*'.

Similarly, UNESCO's criteria for listing on the basis of cultural significance apply to six Australian World Heritage sites. Three sites have unique World Heritage cultural values exhibiting '*an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design*' (e.g. the Royal Exhibition Building and Carlton Gardens in Melbourne) and '*unique artistic achievement and a masterpiece of the creative genius*' (e.g. Sydney Opera House and Aboriginal rock art in Kakadu National Park).

The criteria for listing are regularly revised by the World Heritage Committee to reflect the evolution of the World Heritage concept. Until the end of 2004, World Heritage sites were selected on the basis of six cultural and four natural criteria– whereas now only one set of ten criteria exists (UNESCO 2009). As a result, criteria for which many sites were originally inscribed on the World Heritage List differ from those used in this publication, which uses the current World Heritage selection criteria.

A more detailed list of UNESCO's criteria is summarised in Table 1. Table 2 lists Australia's World Heritage properties against their respective listing criteria or criterion.

2 <http://whc.unesco.org/archive/opguide08-en.pdf>

Table 1. Criteria used to justify World Heritage status

Criterion no.	Cultural criteria [3]
(i)	To represent a masterpiece of human creative genius
(ii)	To exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design
(iii)	To bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared
(iv)	To be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history
(v)	To be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change
(vi)	To be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance. (The Committee considers that this criterion should preferably be used in conjunction with other criteria)
	Natural criteria
(vii)	To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance
(viii)	To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features
(ix)	To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals
(x)	To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation

3 From UNESCO, <http://whc.unesco.org/en/criteria>

Table 2. Australian World Heritage properties and the criterion or criteria used to justify their listing (see Table 1 for definitions)

World Heritage property	Criteria for World Heritage status	
	Natural criteria	Cultural criteria
Kakadu National Park	(vii)(ix)(x)	(i)(vi)
Great Barrier Reef	(vii)(viii)(ix)(x)	
Willandra Lakes Region	(viii)	(iii)
Lord Howe Island Group	(vii)(x)	
Tasmanian Wilderness	(vii)(viii)(ix)(x)	(iii)(iv)(vi)
Gondwana Rainforests of Australia	(viii)(ix)(x)	
Uluṟu-Kata Tjuṯa National Park	(vii)(viii)	(v)(vi)
Wet Tropics of Queensland	(vii)(viii)(ix)(x)	
Shark Bay, Western Australia	(vii)(viii)(ix)(x)	
Fraser Island	(vii)(viii)(ix)	
Australian Fossil Mammal Sites (Riversleigh/Naracoorte)	(viii)(ix)	
Heard and McDonald Islands	(viii)(ix)	
Macquarie Island	(vii)(viii)	
Greater Blue Mountains Area	(ix)(x)	
Purnululu National Park	(vii)(viii)	
Royal Exhibition Building and Carlton Gardens		(ii)
Sydney Opera House		(i)

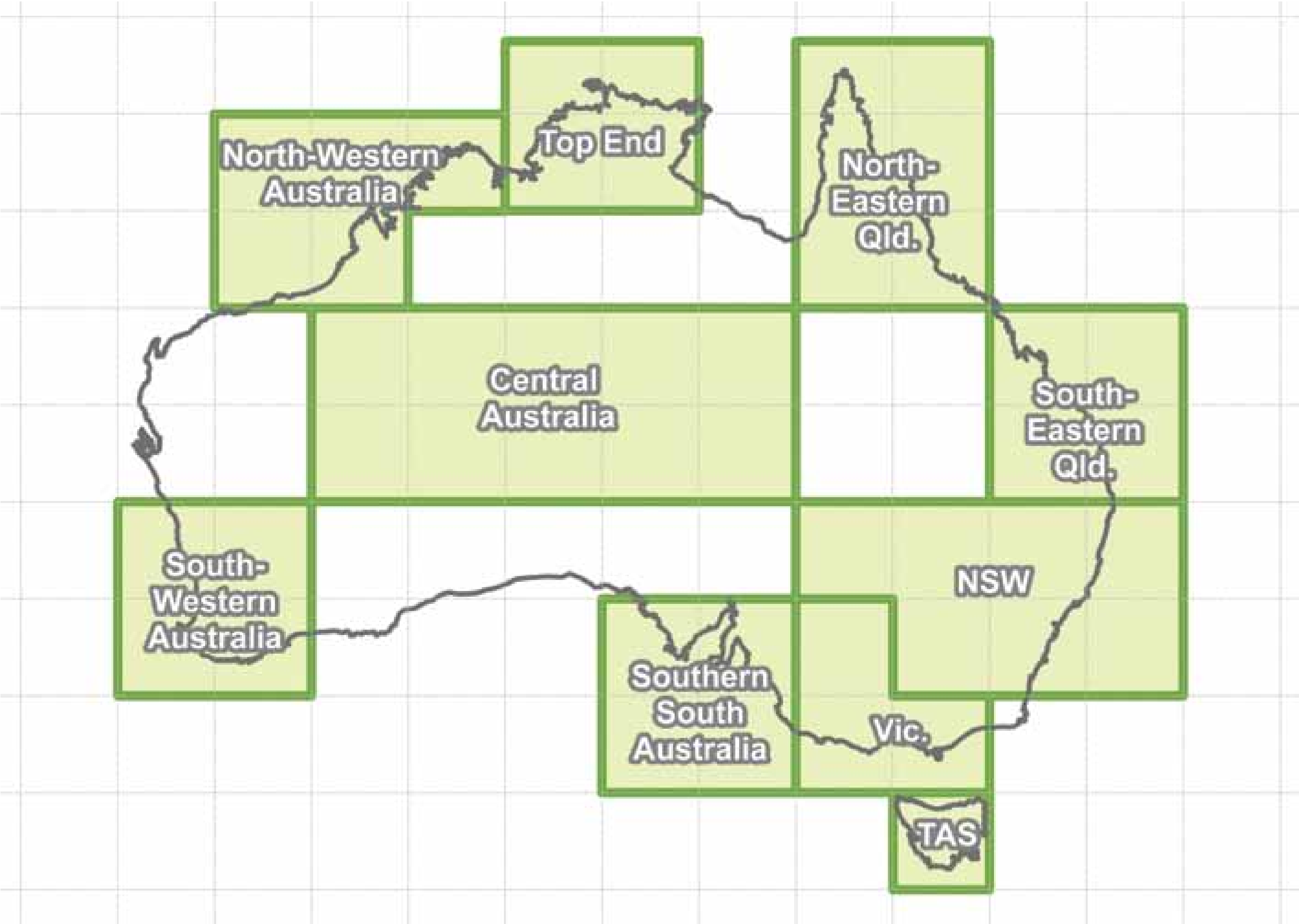
1.3 Climate change scenarios for 2030

The CSIRO has developed a series of Australian climate change scenarios for 2030 relative to 1990 [4], which are outlined in the CSIRO publication *Climate change scenarios for initial assessment of risk in accordance with risk management guidance* (CSIRO 2006).[5] CSIRO 2006 climate change scenarios provide a non-technical description of potential climate impacts across 10 regions in Australia (Figure 2). These climate change scenarios are quoted extensively throughout this paper.

4 Reference year used by the IPCC.

5 These were the scenarios available at the time this study was initiated. A more recent set of scenarios is available at <http://www.climatechangeinaustralia.gov.au/futureclimate.php>

Figure 2. Regions used in the modelling of climate change scenarios (Source: CSIRO 2006)



2. IMPORTANT ASPECTS OF CLIMATE CHANGE FOR WORLD HERITAGE PROPERTIES

In its Fourth Assessment Report 2007, the United Nations IPCC found that 'warming of the climate system is unequivocal' and that levels of greenhouse gas emissions such as carbon dioxide, methane and nitrous oxide in the atmosphere have increased markedly as a result of human activities since 1750. These changes have altered the energy balance in the atmosphere, which results in a warming effect.

The IPCC report found, for example, that more intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought regimes. Changes in sea surface temperatures, wind patterns, and decreased snowpack and snow cover have also been linked to changes in drought occurence.

For the next two decades, a global warming of about 0.2 °C per decade is projected for a range of emissions scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1 °C per decade would be expected.

Rising sea levels and increased acidification of the oceans are also likely. From 1993 to 2003, global mean sea level has been rising at a rate of around 3 mm/yr (Bindoff et al. 2007). Thermal expansion of the oceans and widespread melting of land ice will increase global sea level rise.

2.1 Australian impacts

Australia's average surface temperature has increased by about 0.7 °C since 1900 (IPCC 2007). Recent Australian projections of climate change provide further details to those provided in the IPCC Fourth Assessment Working Group II report. In its *Climate change in Australia: Technical report 2007*, CSIRO and the Bureau of Meteorology (BOM) concluded *'that by 2030, temperatures will rise by about 1 °C over Australia—a little less in coastal areas and a little more inland. Later in the century, warming depends on the extent of greenhouse gas emissions. If emissions are low, warming of between 1 °C and 2.5 °C is likely by around 2070, with a best estimate of 1.8 °C. Under a high emission scenario, the best estimate of warming is 3.4 °C, with a range of 2.2 °C to 5 °C. Rainfall projections for later in the century are more dependent on greenhouse gas emissions. Under a low emissions scenario in 2070, the best estimate of rainfall decrease is 7.5%. Under a high emission scenario, the best estimate is a decrease of 10%.'*

Rainfall patterns are expected to change, with northern Australia likely to receive more rainfall, and southern and south-eastern Australia likely to receive less. Seasonal patterns of falls are also likely to change. Annual average rainfall and streamflows are likely to decrease in southern Australia during winter and spring. Rainfall projections for later in the century are more dependent on greenhouse gas emissions. Under a low emission scenario in 2070, the best estimate of rainfall decrease is 7.5%. Under a high emission scenario, the best estimate is a decrease of 10%. Water supply and quality are likely to be affected by higher temperatures, increased evaporation rates, and changes in amount and patterns of rainfall. As a result of altered seasonality or reduced precipitation together with increased evaporation, water security problems will intensify in southern and eastern Australia. For example, annual streamflow in the Murray Darling Basin is likely to fall 10 to 25% by 2050 and 16 to 48% by 2100.

While there will be more dry days and other seasonal changes, when it does rain, rainfall is likely to be more intense. Climate change projections indicate that there is a likelihood of more extreme weather events (i.e. heavy rainfall and hail, flash flooding, and strong winds) and an increase in more intense tropical cyclones. Extreme weather events are likely to affect most of Australia's World Heritage values, both cultural and natural. Extreme weather events may result in irreversible changes to geological and geomorphologic values. Therefore, important cultural sites such as Aboriginal middens, sea cave deposits, rock art and cave art sites, which rely on the integrity of their underlying landforms (i.e. geological and geomorphologic values), are also likely to be affected.

Regarding natural values, higher sea and land temperatures, sea level rise and ocean acidification, and prolonged drought pose a significant threat to marine and terrestrial biodiversity across Australia's World Heritage estate. Changes in the abundance and distribution of many species are expected, including the expansion of species able to take advantage of the new opportunities (which may especially include invasive species), and reduction or extinction of indigenous plants and animals with limited dispersal capabilities and/or narrow climatic tolerance ranges.

The effects of climate change cannot be considered in isolation. They must be viewed in context with other current threats to Australia's World Heritage values, both natural and cultural. Climate change effects are likely to exacerbate the current problems associated with human-induced changes to the landscape through deforestation, fire [6], urban expansion, water extraction and tourism, as well as non-human factors such as the spread of exotic pests and diseases. Management strategies should strengthen the resilience of natural and cultural values to climate change through management of these more familiar environmental stress factors.

A summary of climate change scenarios for each of Australia's World Heritage properties is shown in Table 3. Potential climate change threats for all of Australia's World Heritage properties have also been summarised (Table 3). These scenarios are based on CSIRO's 2006 climate change projections (CSIRO 2006). See Appendix A for more details.

Table 3. Summary of potential impacts of climate change on Australia's World Heritage properties

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Kakadu National Park	• Rising sea level • Higher temperatures • Changed fire regimes • More intense cyclones • Higher evaporative demand, and reduced runoff into streams and rivers • Threats from a change in disease dynamics and feral animals • Increased carbon dioxide (CO_2) concentrations	• Expansion of mangrove communities • Decline of saltwater-sensitive species (i.e. melaleuca species) • Changes in the spatial zonation of the coastal and floodplain vegetation • Some expansion of woody vegetation possible from increased CO_2, although nutrient availability might be a limiting factor • Higher temperatures and extreme weather events may facilitate the spread and re-emergence of diseases such as malaria, encephalitis and meliodosis • Accelerated erosion from sea-level rise, storm-surge and cyclones • Destruction of wetland communities from intense cyclone activity	Monitoring programs have been ongoing. There is a need to gain a better understanding of the geomorphologic processes and mechanisms associated with saline intrusion. Better stakeholder communication strategy is required. Vegetation response to future climate change is still largely unknown.

6 Fire has always been a natural and cultural phenomenon in the Australian landscape. Research has identified that more intense and frequent fire regimes resulting from climate change have emerged as a major threat to at least half of Australia's World Heritage properties. Increased fuel loads—in association with reduced rainfall, higher temperatures and reduced humidity—are likely to lead to an increase in the number of extreme fire danger days. A change in fire regime is likely to affect both cultural and natural World Heritage values.

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Great Barrier Reef	• Higher sea water temperatures • Sea level rise • Increased carbon dioxide (CO_2) concentrations • Ocean acidification • More intense storms and cyclone activity	• Further coral beaching • Reduced coral growth rates and/or skeletal density due to ocean acidification • Increased mortality in seabirds, turtles and other species attributable to provisioning failure that is consequent on changes to circulation patterns • Changes to rainfall patterns and an increased likelihood of flooding, which affect flora and fauna (e.g. mangroves and seagrass) on reefs, islands and in estuaries • Increases in sea levels affecting nesting (e.g. some birds and turtles) and mangrove reproduction	Uncertainty about the impact of particular aspects of climate change on a location-by-location basis. The Coral Bleaching Response Plan uses an efficient and rapid surveillance system (i.e. satellite and aerial technology) to determine the extent of coral bleaching and better understand the impacts associated with coral bleaching.
Willandra Lakes Region	• Drought • Higher temperatures • Increase in pest numbers • Fire events	• Stream erosion through more severe storms (although this is a naturally occurring process) • Accelerated erosion	Although there is extensive research on how climate change has affected the geomorphology of the Willandra Lakes Region and human habitation in the past, there is an absence of authoritative research analysing how potential climate change might affect the property's World Heritage values in future.

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Lord Howe Island Group	• Sea level rise • Drought • Changes in sea surface temperatures • Changes in the orographic cloud layer • Wave action • Increased carbon dioxide (CO_2) concentrations • Ocean acidification • Marine pest invasions	• Greater impact of wave action on shorelines. Coastal cliffs and rocky shore platforms may undergo extensive erosion from sea-level rise and severe storm events • A change in mossy cloud layer may lead to reduced occult precipitation [7] and changes in the hydrological regime • Changes in marine population numbers • Threat to seabird populations from changes in the abundance or distribution of prey • Coral reefs are likely to be affected by ocean acidification • Loss of endemic fauna and flora	Potential biological and hydrological impacts resulting from a change in the mossy cloud layer requires further investigation. There are some opportunities for collaborative research in this area (e.g. Wet Tropics of Queensland). Tighter controls over illegal and recreational fishing. Long-term studies of some key indicator species are needed. A better understanding of the extent of genetic diversity among endemic fish species might provide insight into the adaptive capacity of some species to adapt to climate change impacts.

7 Water derived from fog, dew and cloud, not recorded in rain gauges.

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Tasmanian Wilderness	• Temperature rise • Sea level rise • Extreme weather events and flash flooding • Changes in fire frequency and intensity • Although evaporation rates will increase, streamflow response is likely to be unpredictable • Reduction in snow cover	• Extensive erosion is regarded as a major concern to the geoconservation (non-living) values of the area, particularly to the Central Plateau • Climate change is likely to result in a rise in the climatic treeline. It is likely that the elevation of the treeline will increase some 250 to 300 m above the present treeline • Wildfires threaten alpine and rainforest vegetation • Unplanned fires (from natural and other ignition sources) in buttongrass moorlands are likely to become more widespread • Extensive loss of organic peat soils from the frequent burning of button grass moorlands • Rising sea levels and large storm-surge events pose a significant threat to the integrity of the coastline. These threats are likely to result in physical changes (erosion, rockfalls and slumping) to the coastal zone, dramatically changing the geomorphology of coastal regions • With rising sea level, the depth of water above subsurface vegetation communities will increase, almost certainly resulting in a reduction of available light	There is a lack of traditional and historical knowledge of the effects of fire on these landscapes. Changing fire regimes will have a direct impact on the flora, and further beneficial work could be undertaken on the effect that the loss of organic soil horizons would have on the potential for the communities to re-establish. Changes in the periglacial sorted ground on the Central Plateau may provide a good indicator of temperature rise. Changed fire regimes that are influenced by climate change are likely to be detrimental to many species, prompting the need to investigate the relationship between extreme fire events and implications for species' abundance and distribution. Impacts of climate change on archaeological sites require further investigation.

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Gondwana Rainforests of Australia (CERRA [8])	• Higher temperatures • Increased carbon dioxide (CO_2) concentrations • Periods of prolonged drought • A rise in the orographic cloud layer • Exacerbation of fire regimes that are inappropriate to maintenance of rainforest species	• Further habitat fragmentation • Frequent fires may threaten fauna and flora populations, and result in habitat loss • The cool upland subtropical forests are at greatest risk from higher temperatures and lower rainfall • There are two groups of Gondwanan rainforests under threat from climate change: the microphyll fern forests, typically dominated by *Nothofagus moorei* (Antarctic beech); and the simple notophyll evergreen vine forests, generally dominated by *Ceratopetalum apetalum* (coachwood) • Loss of species with low dispersal ability and/or specific habitat preferences	Some biodiversity studies are planned. These studies will attempt to define and understand the patterns of biodiversity change along altitudinal gradients. A bioclimatic model for the chytrid fungus has not been produced and would be a valuable tool to assess the potential geographic spread of this disease.
Uluṟu-Kata Tjuṯa National Park	• Temperature increase • Droughts are likely to become more frequent • Extreme weather events and flash flooding • Wildfires	• Climate change will have some effect on the morphology of the region, including spalling of arkose sediments and cavernous weathering • Cultural expression would appear to be directly threatened by climate change; if hunting is a key activity, any substantial reductions in fauna populations associated with climate change will erode cultural values	Much of the literature centres on particular species or interactions. Arguably there is a need for a more wide-ranging analysis that has an interdisciplinary focus and integrates life sciences aspects with some exploration of cultural questions and communication with the traditional owners of the region.

8 Previously known as the 'Central Eastern Rainforest Reserves of Australia', or CERRA, from 1994 until renamed with the current name in 2007.

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Wet Tropics of Queensland	• More intense cyclone and storm activity • Rising sea level • A rise in the orographic cloud layer • Changed fire regimes • Higher temperatures • More frequent drought • Increased evaporation • Increased carbon dioxide (CO_2) concentrations	• Reduction in occult precipitation may lead to significant hydrological changes • Reduction in streamflow • Rainforests above 800 m, which contain the vast majority of the region's endemic fauna, are at greatest risk from global warming • More vegetation damage from high, destructive winds	Options for translocation and restoration of species habitats, particularly in higher altitudes. Better water management strategies need to be developed, especially if annual rainfall is to decline as climate projections suggest. The downstream impacts from changes in the orographic cloud layer should be examined and modelled.
Shark Bay, Western Australia	• Higher sea water temperatures • Sea level rise • Increased carbon dioxide (CO_2) concentrations • More frequent severe droughts, which affect conditions on land • Ocean acidification • More intense storms and cyclone activity	• Alteration of seagrass habitats (changed salinity and more frequent storms) • The impact of raised temperatures and increased CO_2 is uncertain; higher levels may increase primary production of biomass • Changed relationships between sharks and other marine species as a result of changes to the Leeuwin Current • Attributes such as raised temperatures, storms and increased CO_2 levels will affect particular habitats (such as those occupied by reptiles and terrestrial mammals) • Increased sea temperatures may favour a southern movement of tropical marine life • Increased temperatures would appear likely to increase the frequency and effectiveness of predation by the tiger shark	There are uncertainties about the effect of climate change on currents along the continental shelf and fish stocks, in particular the Leeuwin Current. There is significant access to and commercial use of Shark Bay and its environs (including minerals extraction; prawn fishing; and ecotourism centred on migratory whales, turtles and dugong). Pressure from those activities is likely to increase with, for example, ecotourism becoming more intensive if climate change trends increase and if consumers believe that their window to 'see the dugong before they disappear forever' is closing.

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Fraser Island	• Temperature rise • Changed fire regimes • Increased dune erosion • Drought • Water extraction and changes in hydrology • Sea level rise • Increased carbon dioxide (CO_2) concentrations	• Changes in surface water and groundwater hydrology • Accelerated dune erosion mainly from wind and rainfall action • Change in vegetation cover and loss of rainforest species • Higher water temperatures can affect chemical, physical and biological processes in lakes • Changed fire regimes may pose a major threat to the island's fauna through the destruction of vital habitats	Excessive visitation has placed pressure on water resources. There may be a need to limit visitation to the island. The optimum fire frequency that will still enable the maintenance of peat development and the other species it supports has not been determined. There is little palynological data from lakes at Fraser Island that could provide a window on past climatic events.
Australian Fossil Mammal Sites (Riversleigh and Naracoorte)	• Increased frequency of storm events • Higher evaporative demand • Higher temperatures	• Greater erosion through flash flooding • Changes in rainwater pH	The effects of climate change on fossil sites have not been discussed extensively in authoritative, peer-reviewed literature. A more detailed examination is desirable.

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Heard and McDonald Islands	• Rise in sea surface temperature • Deglaciation • Sea level rise • Changed ocean water chemistry • Successful establishment of introduced species	• Continued warming is expected to lead to further glacial retreat and consequent exposure of new ice-free ground or waterbodies • Population growth of some species may be at the expense of vulnerable species • With pronounced warming, there is an increased likelihood that non-native species arriving at the islands will survive and may become invasive if they are well-enough established	A continued warming trend is likely to further impact on species distribution and abundance in a way that is difficult to predict. As identified in the management plan for the property, ongoing monitoring will allow for continued evaluation of the impact of climate warming on the World Heritage values. As identified in the management plan, the relative absence of human disturbance means there is a unique opportunity to conduct studies on the response of species to climate change in the absence of other anthropogenic influences (e.g. land clearing, occupation by alien species, urban development).

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Macquarie Island	• Likely declines in rainfall • Rise in sea surface temperature • Sea level rise • Changed ocean water chemistry • Introductions of pests and diseases	• Some fundamental changes in the limnological condition of subantarctic lakes and ponds are likely from global climate warming • As temperatures increase, there is likely to be a higher rate of photosynthetic activity and productivity for most plant species on the island • Several plant species have optimum temperatures for photosynthesis well above the current ambient temperature. The introduction and establishment of woody vegetation could also occur in a timespan of 100 years if temperatures continue to rise at the current rate • Changes in sea surface temperatures and a shortfall in food resources could be contributing factors leading to the decline of some penguin populations	The capacity of rockhopper penguins to maintain population numbers, and for king penguin populations to increase in size, is unclear and requires further investigation. Several studies have linked rockhopper penguin declines on other sub-Antarctic islands to a change in food production correlated with a change in the extent of sea ice. Although some fundamental changes in the limnology of lakes, tarns and pools can be expected from higher temperatures and UV-B exposure, the long-term impacts are difficult to predict. There needs to be an increased emphasis on biosecurity and specific on-ground surveys for alien species.

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Greater Blue Mountains Area	• Higher temperatures • Greater frequency and intensity of fire • Greater erosion and spalling processes • Change in seasonal rainfall • Higher evaporative demand • Increased carbon dioxide (CO_2) concentrations	• The extinction of some eucalypt species from fire and higher temperatures • Possible contraction in all plant communities • Vertebrates affected by a change in forest cover • Rocky habitats may also prove to be vulnerable due to rock instability from wildfires • Change in leaf chemistry in some plant species • Reduced streamflow and higher temperatures could affect fauna and flora • More intense and more frequent fires may be potentially fatal to plant and animal species, in particular those species that do not have the ability to migrate • Heat from fire can also lead to the deterioration of karst environments (comprised of carbonate stone) by stimulating erosion and changes to chemical processes	The adaptive threshold response of many fauna species to changes in vegetation cover following environmental disturbance (i.e. more intense and/or more frequent fire events, changes to seasonal rainfall and temperature) is unknown and requires further investigation. A lack of knowledge of the ecology of the approximately 1,500 plant species and the many thousands of fauna species of the property is critical. The impacts of fire coupled with changes in weather/climate—e.g. rainfall, severe storm events, wind—is critical and needs to be addressed. Urban expansion on the fringe of the natural area will exacerbate management challenges, e.g. for fire. More systematic studies are underway to examine the impact of fire on biodiversity of the Greater Blue Mountains.

World Heritage property	Potential climate threats	Potential impacts	Management/contingency plans/knowledge gaps
Purnululu National Park	• Temperature increase • More intense cyclone activity • Extreme weather events and flash flooding • Droughts are likely to become more frequent and severe • Wildfires	• It is unlikely that climate change in the immediate term will fundamentally erode the aesthetic attributes of Purnululu, although uncertainties remain • Heightened exposure to recurrent wildfires in the spinifex plains to the east in the absence of traditional fire management regimes • Cyanobacteria are not uniform and some species are more drought tolerant than others, and less affected by temperature changes • Wildfire may increase the weathering rate of the karst	There is uncertainty about the direct and indirect impacts of climate change on the cyanobacteria species that create the bands in the karst formations and on the formation of crusts. A fire in Purnululu has apparently removed the bands of cyanobacteria from the karst.
Royal Exhibition Building and Carlton Gardens	• Temperature rise • Drought	• Increased CO_2 levels would not appear to pose fundamental problems for vegetation in the gardens • Possibility of accelerated deterioration of the physical fabric of the building. English Heritage has undertaken some studies on this	Some decision-makers will be unaware that climate change may affect the gardens; others will disagree about priorities relative to other locations such as the Royal Botanic Gardens.
Sydney Opera House	• Sea level rise and flooding due to storm surge	• Sea level rise affecting building structure and fabric	The effect of sea level rise on the building's structure and fabric is worthy of assessment.

3. SUMMARY OF POTENTIAL IMPACTS OF CLIMATE CHANGE ON AUSTRALIA'S WORLD HERITAGE PROPERTIES AND VALUES

Australia's World Heritage properties and their values are diverse, and will not be affected equally by climate change. Some properties, such as the Great Barrier Reef and the Wet Tropics of Queensland, are highly sensitive, whereas others, such as Naracoorte (Australian Fossil Mammal Sites), are likely to be less susceptible to the effects of climate change. Climate change may or may not impact on the value of a World Heritage property as assessed under UNESCO's criteria.

The literature on potential climatic impacts on individual values is extremely uneven. This is not surprising, given the uncertainty about climate change projections at a regional scale and the lack of information on potential impacts on biological or physical systems. It also reflects the fact that, globally, climate change impacts research is a relatively new and evolving field. Researchers also tend to focus on particular values (i.e. species taxonomy and classification) and interactions, rather than broader relationships between values and the impacts climate change will have on those values. However, a salient feature of this review is that such 'patchiness' inhibits an authoritative overall assessment across the properties.

Palaeoclimatic studies have revealed that some of Australia's World Heritage properties have undergone periods of considerable change through a series of glacial cycles. These studies provide a clear indication that the values of these World Heritage properties will continue to change in response to both natural and non-anthropogenic climate change.

The following discussion identifies some of the direct (e.g. higher temperatures, increased carbon dioxide (CO_2) concentrations) and indirect (e.g. fire, pests, diseases) impacts of climate change on Australia's World Heritage properties and their values. Information is summarised in Appendix C.

The following discussion is organised in terms of the impacts on the natural and cultural values identified in the UNESCO World Heritage criteria (see Section 1.2 above). The discussion of natural heritage values is divided in two, discussing impacts on areas listed on their basis of their biodiversity values in Section 3.1.1 and on their aesthetic and geological process values in Section 3.1.2. The discussion on cultural values is similarly split between two sections.

3.1 Potential impacts on natural heritage values

3.1.1 Potential impacts on World Heritage properties listed as meeting either or both natural heritage criteria (ix) and (x)

Australian World Heritage properties that meet either/both criteria (ix) and (x) (Box 1) include:

- Kakadu National Park
- Great Barrier Reef
- Lord Howe Island Group
- Tasmanian Wilderness
- Gondwana Rainforests of Australia
- Wet Tropics of Queensland
- Shark Bay, Western Australia
- Fraser Island
- Australian Fossil Mammal Sites
- Heard and McDonald Islands
- Greater Blue Mountains Area.

Box 1. Natural heritage criteria (ix) and (x)

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Criterion (x): To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Higher temperatures, increased CO_2 concentrations, ocean acidification and prolonged drought are likely to have a major impact on the natural values of ecological and biological significance of Australia's World Heritage properties. The indirect impacts of climate change (e.g. on fire and invasive species) are also likely to have significant impacts on these values. Examples are provided below.

Temperature

It is estimated that a 1 °C rise in temperature could result in a 50% decrease in the area of highland rainforests in the Wet Topics of Queensland by 2030 (Hilbert et al. 2001). They could vanish completely with only a 2 °C temperature rise. The loss of these remnant rainforests would result in the loss of the core habitats of many endemic vertebrate species. At least 10 endemic bird species in the Wet Tropics of Queensland are highly dependent on cool habitats for their survival and are restricted to higher elevations where cooler conditions prevail. A 3.5 °C increase in temperature combined with variable rainfall would result in the total loss of the core habitats of about 30 endemic vertebrates (Williams et al. 2003).

A rise in temperature could also have a direct impact on animals whose sex is determined by temperature (temperature sex determination, or TSD). For example, the eggs of reptiles and amphibians depend on certain nest temperatures for sex determination. Consequently, a rise in atmospheric temperature could have a direct bearing on nesting temperature, and hence reproduction and phenotypic determination (Webb et al. 1986). Those reptiles with a limited climatic range and distribution, such as the rare Pedra Branca skink (*Niveoscincus palfreymani*), could be particularly vulnerable to a rise in temperature. The habitat of this species is confined to an isolated rock island, Pedra Branca, which is situated 26 km off the south-east coast of Tasmania, within the boundaries of the Tasmanian Wilderness. At times, the island supports as few as 250 individuals.

A further consequence of higher temperature is an extension of the ice-free season for waterbodies on Australia's World Heritage subantarctic islands (Macquarie Island, Heard and MacDonald Islands). Observations indicate a strong correlation between an increase in temperature and glacial retreat on Heard Island. This has resulted in exposure of large areas of bare ground previously covered by ice. These landscape changes have enabled fauna and flora to colonise newly-exposed areas, which change the distribution and abundance of plant and animal species (AAD 2005). Global warming is likely to impact further on species distribution and abundance, as well as competition between species, in a way that is difficult to predict.

Carbon dioxide

Increased atmospheric CO_2 concentrations are also likely to impact on plant species through a process known as the 'CO_2 fertilisation effect', whereby plant growth is accelerated under high concentrations of CO_2. However, this may be countered by water and nutrient availability. Increased CO_2 concentrations are likely to change the competitive nature of plant species. An increase in CO_2 is also likely to affect the nutritional value and chemical composition of foliage, which in turn is likely to affect some leaf-eating mammals such as the Lemuroid ringtail possum (*Hemibelideus lemuroides*) (Kanowski 2001).

Rainfall

Changes in rainfall and a rise in the basal altitude of the orographic cloud layer are likely to have a significant impact on the natural values of Australia's World Heritage properties. Most of Australia's World Heritage properties have experienced a decline in rainfall over the past 35 years. Current CSIRO projections indicate that mean annual rainfall will continue to fall in many regions across Australia. If annual rainfall remains unchanged, evaporation is likely to be higher (CSIRO 2006), resulting in drier conditions.

A potential rise in the average basal altitude of the orographic cloud layer due to global warming (Pounds et al. 1999) is an issue of concern for a range of values across a number of World Heritage properties, in particular in the Wet Tropics of Queensland and the Lord Howe Island Group. The orographic cloud layer envelops the mountain summits of these World Heritage properties, and provides an essential source of water for many high-altitude plants and animals by a process known as 'cloud stripping' by high-altitude rainforests. Very little is known about the hydrology of cloud stripping and the resulting precipitation derived from this process. However, it is fairly certain that a rise in basal altitude of the orographic cloud layer would exacerbate the effects of long-term drought (Still et al. 1999), resulting in serious consequences for many plant and animal species. Microhylid frogs [9], for example, rely on cloud mist for their long-term survival. The disappearance of about 20 frog species in the highland forests of Monteverde, Costa Rica, was probably due to changes in the extent of mountain mist following an increase in surface temperature (Pounds et al. 1999).

Tropical cyclones and extreme weather events

Research has shown that there has been an increase in the destructiveness of cyclones since the 1970s, which correlates with the observed increase in sea surface temperature (Emanuel 2005). Tropical cyclones are common in Kakadu National Park, the Great Barrier Reef and in the Wet Tropics of Queensland. Current projections indicate that cyclones are expected to be less common but more intense (CSIRO 2006), which may inflict greater physical damage to vegetation including the uprooting of trees by destructive winds. High-intensity cyclones may inflict greater damage on certain vegetation types than on others. Eucalyptus trees taller than 9 m are particularly prone to wind damage (Williams & Douglas 1995). The uprooting of trees can also lead to increased erosion during periods of intense rainfall. Invasive species such as climbing vines can also be favoured in the aftermath of tropical cyclones.

Increased sea surface temperatures, changes in ocean circulation and ocean acidification

The impacts of rising sea surface temperatures and ocean acidification will most likely have catastrophic consequences for marine organisms such as coral and the species dependent on these keystone species, as well as for calcifying organisms such as plankton, sea urchins and coral reef systems (Feely et al. 2004). Acidification takes place via the reaction of dissolved carbon dioxide with water to produce carbonic acid which, in turn, increases acidity. The resulting acidification could prevent calcifying organisms—such as corals, shellfish and some species of phytoplankton—from producing calcium carbonate and thus prevent shell formation. Coral communities around the Lord Howe Island Group (which are the southernmost true coral reefs in the world) and the Great Barrier Reef are likely to be affected if the oceans become more acidic. To date, there have been no experimental studies examining the sensitivity of cold-water coral reef systems, such as those in the Lord Howe Island Group, to CO_2-induced ocean acidification. However, it is expected that the acidification will affect the recruitment of cold corals more than their warm-water counterparts because the carbonate saturation state is generally lower at higher latitudes than at lower latitudes (i.e. Great Barrier Reef) (The Royal Society 2005).

9 Microhylid frogs lay their eggs on the forest litter and therefore require a constant source of moisture from the cloud stripping process to prevent desiccation of eggs and larvae.

Some scientists (e.g. McMahon et al. 2005; Priddel et al. 2006) have hypothesised that the decline in seabird populations in the Lord Howe Island Group, and of elephant seals at Macquarie Island, may be related to a change in food supply associated with changes in the marine environment in general. In the Pacific region, researchers have associated changes in fish stocks with increased El Niño-Southern Oscillation (ENSO) cycle activity (Bunce et al. 2002). A change in the abundance or availability of food brought about by shifts between two climatic systems, namely the Antarctic Circumpolar Wave (ACW) and the ENSO, could be one explanation for the decline in elephant seal numbers (McMahon et al. 2005). These systems influence the extent of sea-ice retreat (Kwok & Comiso 2002) and the recruitment of krill, which is a source of food for many marine predators (Loeb et al. 1997). However, the connection between global warming and changes in the earth's climatic systems, such as ENSO, is still ambiguous. According to IPCC (2007), it is unclear how the frequency and intensity of El Niño events will respond to global warming.

Chemical and physical changes to the coastal zone

The World Heritage properties of Kakadu National Park, Tasmanian Wilderness, Shark Bay, Fraser Island, Lord Howe Island Group, Macquarie Island, Heard and McDonald Islands, Great Barrier Reef and Wet Tropics of Queensland are likely to be affected to varying degrees by sea level rise. Rising sea levels and large storm-surge events pose a significant threat to the integrity of the values of these World Heritage properties. Changes in salinity and physical changes to the coastal zone of some World Heritage properties may have significant implications for terrestrial and marine habitats.

Kakadu and Shark Bay will face a more immediate threat from further sea level rise, resulting in an increase in flooding of low lying areas. Remnant mangrove swamps provide evidence of past sea level rise in Kakadu and could aid in predicting future impacts to river systems resulting from rising sea levels. The coastal plains of Kakadu are about 0.2 to 1.2 m above the high-tide water mark (Eliot et al. 1999). Large numbers of buffalo during the mid-1980s accelerated the erosion of levee banks, which led to considerable displacement of alluvium and a subsequent increase in salinity (Cobb et al. 2000). Current projections indicate that sea levels around Kakadu National Park will rise by at least 8 cm, and possibly up to 30 cm, by 2030 (Eliot et al. 1999). A rise in sea level of this magnitude is likely to lead to a further extension of tidal rivers and pose a significant threat to freshwater wetland systems, resulting in a decline in saltwater-sensitive plant species such as melaleuca. It is believed that sea level rise resulting from global warming has already led to changes in Kakadu National Park's terrestrial ecosystem. For example, aerial studies have shown that over the past 40 years there has been a change in the distribution of mangrove communities (Lucas et al. 2002).

Indirect impacts—fire

More extreme and more frequent wildfires are likely to have a major impact on fire-sensitive forest communities (i.e. rainforests and alpine forests) and the organisms that they support. The rainforests of the Greater Blue Mountains Area provide a microclimate for primitive plant species with Gondwanian affinities, such as the Wollemi pine (*Wollemia nobilis*). This species, originally thought to be extinct, is found in only one specific location in the Greater Blue Mountains Area. Although the effect of fire on the Wollemi pine remains largely unknown, catastrophic fire events could threaten remaining stands (DEC 2005). A change in fire regime may affect fire-sensitive conifer species—including Huon pine (*Lagarostrobos franklinii*), Pencil pine (*Athrotaxis cupressoides*) and King Billy pine (*Athrotaxis selaginoides*)—found in montane and subalpine areas of the Tasmanian Wilderness (Parks and Wildlife Service 2004). An increase in the extent and severity of peat fires in World Heritage properties such as Fraser Island and the Tasmanian Wilderness is also of major concern. Extensive peat fires can often burn for weeks.

Excessive human visitation, exotic pests and diseases

It is not known the extent to which excessive visitation and exotic pests and diseases are likely to exacerbate future climate change effects. The threat of changes in disease dynamics brought about by climate change is a major concern, because pests and diseases are, by nature, opportunistic. Climate change might modify the incidence and geographic range of some vector-borne diseases (McMichael et al. 2006). Also, the response of alien and invasive plant and animal species to climate change remains largely unknown. However, many researchers believe that climate change will favour their existence and domination. The spread of invasive species, such as the notorious cane toad into the wetland systems of Kakadu National Park, is also of major concern to park managers. Expansion of invasive species has been reported in other World Heritage properties. Heard Island's only recorded alien invasive plant species, *Poa annua*, showed dramatic expansion between 1987 and 2000, which is attributed to an increase in seal disturbance and climatic change factors (Scott & Kirkpatrick 2005).

The impacts of excessive human visitation to Australia's World Heritage sites are likely to exacerbate the effects of climate change. For example, groundwater extraction on Fraser Island has been described as 'potentially high risk' by the Fraser Island World Heritage Area Scientific Advisory Committee (EPA 2004) and has emerged as an important factor that may affect the integrity of the values of the World Heritage property such as patterned swampy mires [10] and fens that derive their water and nutrient supply from the watertable.

3.1.2 Potential impacts on properties listed as meeting any/all natural heritage values in criteria (vii) and (viii)

Australian World Heritage properties that meet any/all criteria (vii) and (viii) (Box 2) include:

- Kakadu National Park
- Great Barrier Reef
- Willandra Lakes Region
- Lord Howe Island Group
- Tasmanian Wilderness
- Gondwana Rainforests of Australia
- Uluṟu-Kata Tjuṯa National Park
- Wet Tropics of Queensland
- Shark Bay, Western Australia
- Fraser Island
- Australian Fossil Mammal Sites
- Heard and McDonald Islands
- Macquarie Island
- Purnululu National Park.

Box 2. Natural heritage criteria (vii) and (viii)

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

10 The location of mires at sub-tropical latitudes is rare, as they are normally found in cold climates where lower temperatures and slower decomposition rates are conducive to peat formation. Mires that derive their water and nutrient supply from the watertable (as opposed to bogs, which derive their water from rainfall) are referred to as fens.

The geological and geomorphologic values of World Heritage properties are particularly vulnerable to extreme weather events (i.e. more intense cyclones), rising sea levels and the effects of fire.

Extreme weather events

Extreme weather events may result in irreversible changes to geological and geomorphologic values. Climatic impacts on landforms represent major stages of the earth's history, occurring over millions of years. World Heritage properties such as Purnululu and the Willandra Lakes Region were nominated for World Heritage status because of climate-induced impacts on their distinctive landforms. However, the extent to which climate change will significantly affect these unique 'landform values', such as the banded [11] sandstone beehive structures found in Purnululu, is difficult to predict.

However, some landforms are more susceptible to damage from extreme weather events, such as the threat of increased erosion triggered by severe storm events in regions that have already become vulnerable due to the impacts of overgrazing and fire. For example, erosion is currently regarded as a major concern to the geoconservation values of the north-eastern portion of the Tasmanian Wilderness, particularly on the Central Plateau, where alpine sheet erosion has been described as the 'worst alpine erosion in Australia' (Parks and Wildlife Service 2004). Heat from fire can also lead to deterioration of the carbonate stone of karst environments by stimulating erosion and changes to chemical processes.

Rising sea levels

Rising sea levels and large storm-surge events pose a significant threat to the integrity of the coastline of Australia's World Heritage properties. These threats are likely to result in physical changes (erosion, rockfalls and slumping) to the coastal zone, which dramatically change the geomorphology of coastal regions (Sharples 2006), in addition to inundation of low-lying areas. Over the past few years, managers of the Tasmanian Wilderness have noticed a substantial increase in the extent of beach erosion, with many beaches exhibiting faster rates of beach loss than occurred during the last century. In Lord Howe Island Group there is the potential for crumbling coastal cliffs and rocky shore platforms in response to sea level rise and/or changes in wave characteristics (Dickson & Woodroffe 2002).

Indirect impacts—fire

Changed fire regimes could also have devastating impacts on geomorphic or physiographic features. More extreme and frequent fire events are likely, which can alter vegetation cover and lead to an increase in erosion.

Sandstone outcrops and rocky cliff faces are more likely to become weak and brittle from extreme heat generated by intense fire storms, thus predisposing these natural features of the landscape to 'fire induced rock weathering' impacts such as spalling (flaking) (Shakesby & Doerr 2006). Rock measurements conducted in the Greater Blue Mountains Area have revealed that spalling can result in as much as 6 g of dislodged rock per square metre of fire exposed sandstone (Adamson et al. 1983). Heat from fire can lead to the deterioration of karst environments by stimulating erosion and changes to chemical and hydrological processes.

11 Sandstone towers marked by horizontal bands of cyanobacteria. Cyanobacteria are single-celled photosynthetic microorganisms.

3.2 Potential impacts on cultural heritage values

3.2.1 Potential impacts on properties listed as meeting any/all cultural heritage listing criteria (iii) to (vi)

Australian World Heritage properties that meet any/all criteria (iii) to (vi) (Box 3) include:

- Kakadu National Park
- Willandra Lakes Region
- Tasmanian Wilderness
- Uluṟu-Kata Tjuṯa National Park.

Box 3. Cultural heritage listing criteria (iii) to (vi)

Criterion (iii): To bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared.

Criterion (iv): To be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history.

Criterion (v): To be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change.

Criterion (vi): To be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance.

The preservation of unique cultural values including Aboriginal middens, sea cave deposits and archaeological sites (e.g. Pleistocene and Holocene burial sites) is highly dependent on the maintenance and protection of their underlying landforms from climate change impacts. Particular spiritual values, for example, appear to be timeless and the loss of sacred sites can be devastating to a community. Some cultural expression would appear to be directly threatened by climate change; if hunting is a key activity, any substantial reductions in fauna populations associated with climate change will erode cultural values.

Chemical and physical changes to the coastal zone

Apart from their intrinsic geomorphic values, the coastal regions of Kakadu National Park and the Tasmanian Wilderness contain significant Aboriginal cultural values. These unique values are reflected in features such as middens and sea cave deposits. Their preservation is dependent on the maintenance and protection of their underlying landforms from climate change impacts (i.e. excessive erosion, sea level rise and storm-surge events). Clearly, these non-renewable cultural features will require significant considerations regarding their management.

Rainfall and extreme weather events

Climate change projections indicate an increase in extreme weather events and flash flooding that will affect Australia's World Heritage properties containing unique cultural values. Although erosion is a natural process, accelerated erosion (wind, stream and sheet erosion) may be detrimental to cultural heritage, including archaeological sites (e.g. Pleistocene and Holocene burial sites in the Willandra Lakes Region). An increase in severe storms, flash flooding and cyclones could also affect access to sacred sites.

Indirect impacts—fire

Fire behaviour is likely to change as result of global warming, resulting in more extreme fire danger days. During the dry season, wildfires create large quantities of smoke, dust and black ash that contaminate the atmosphere and result in the formation of highly acidic rain during tropical storms (Watchman 1991). Proper fire control strategies can help to reduce the destructive force of wildfires. Fire control programs in Kakadu involve traditional owners at all stages, including planning, execution and monitoring. Programs now are very much influenced by Indigenous burning practices (a World Heritage value—*the ongoing, active management of the landscapes by Aboriginal people through the use of fire*). While ongoing monitoring in Kakadu National Park has shown that past fire management practices have not been optimal for the environment, this information has contributed significantly to improved fire management practices.

3.2.2 Potential impacts on properties listed as meeting either/both cultural heritage listing criteria (i) and (ii)

Australian World Heritage properties that meet either or both of these cultural heritage listing criteria (i) and (ii) (Box 4) include:

- Kakadu National Park
- Royal Exhibition Building and Carlton Gardens
- Sydney Opera House.

Box 4. Cultural heritage listing criteria (i) and (ii)

Criterion (i): To represent a masterpiece of human creative genius.

Criterion (ii): To exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design.

These last two cultural criteria relate to '*an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design*' (i.e. Royal Exhibition Building and Carlton Gardens in Melbourne) and '*a masterpiece of the creative genius*'; namely Sydney Opera House and rock art in Kakadu National Park. CSIRO climate change projections for Sydney and Melbourne indicate a 0.5–1.1 °C increase in temperature by 2030 and a decline in annual rainfall. Projections also indicate that there is the likelihood of extreme weather events and prolonged drought (CSIRO 2006). For Kakadu National Park, there is also a tendency for more extreme storm events with an increase in the frequency of severe droughts (CSIRO 2006). Projections indicate that tropical cyclones are likely to become more intense with higher wind speeds (5–10% increase) (CSIRO 2006).

Rainfall and extreme weather events

Higher temperatures and changes in humidity—as well as extreme weather events including wind, severe rain, lightning and hail—can have a direct impact on the fabric of buildings and culturally significant gardens. Changes in rainfall (prolonged drought or excessive rainfall) can also affect building fabric, vegetation and soil chemistry (UNESCO 2006). Soils containing high clay content can, potentially, result in serious cracking during prolonged droughts. Timber buildings may become more vulnerable to an increase in pest and biological infestations. Newer buildings made from concrete, steel and tiles (e.g. Sydney Opera House) are likely to be more resilient to these climatic factors than older buildings constructed from brick, timber, steel and slate (e.g. Royal Exhibition Building).

The rock art sites in Kakadu National Park represent '*a masterpiece of human creative genius*', and are considered one of the greatest concentrations of rock art in the world. Without doubt, rainwater is the primary agent responsible for the deterioration of rock art (Pearson 1978; Pearson & Swartz 1991). Rainwater flowing over rock surfaces can result in extensive rock art damage, although the destructive impacts of water can be lessened through the use of silicone drip lines that divert water away from rock art surfaces.

Historically, extensive flooding has had a devastating impact on rock art and archaeological sites (Rosenfeld 1985). Rock art values could be at risk from an increase in rainfall in northern Australian sites (such as Kakadu National Park). Extreme fire events also lead to rock flaking and soot accumulation (Pearson 1978).

4. FLOW-ON EFFECTS FOR INDUSTRY AND SOCIETY

Apart from the physical threats of climate change, there will inevitably be considerable social, economic and cultural effects, with many communities either forced to adapt to change or to migrate elsewhere (UNESCO 2006).

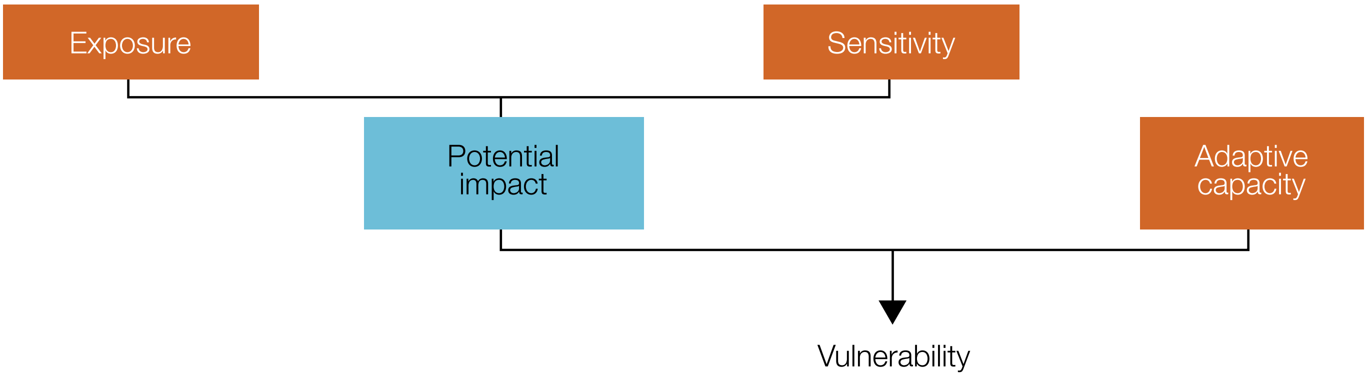
The tourism industry is likely to be hit hardest by climate change. Tourism accounts for almost 13% of total employment in the Northern Territory, 8% in Tasmania (STCRC 2007) and 55% on Lord Howe Island (TTF Australia 2007). Clearly, those industries that rely on World Heritage properties as their main source of tourist revenue are likely to be impacted the most by the effects of climate change. If the Great Barrier Reef were to vanish (which is much less likely than to change), there would be no *unique universal attraction* and therefore tourist operators providing trips to the reef would lose business. There would also be flow-on effects to other industries providing services in accommodation, food, fuel, transport, sport fishing and recreation (TTF Australia 2007).

Furthermore, the marketing of Australia as an attractive and exciting international destination relies on the promotion of a ‘key tourism experience’ (TTF Australia 2007) supported by the natural values of its World Heritage properties. Approximately $23 billion was spent in 2006 by tourists on ‘nature-based’ adventures in places such as Kakadu National Park, Shark Bay, Great Barrier Reef, Tasmanian Wilderness and Fraser Island (TTF Australia 2007). The Tourism and Transport Forum of Australia considers measures to ‘*preserve Australia’s ecological diversity to be a top priority for the Action Plan on Climate Change*’. The *National Long-Term Tourism Strategy Discussion Paper* is available from the Department of Resources, Energy and Tourism, and will inform preparation of a National Long-Term Tourism Strategy, scheduled for completion in mid-2009.

5. ADAPTATION TO IMPACTS

The IPCC defines vulnerability as '*the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change*' (IPCC 2001). It is a function of exposure, sensitivity and adaptive capacity, as illustrated in Figure 3.

Figure 3. Components of vulnerability (Source: Allen Consulting Group 2005)



Adaptive capacity includes both autonomous (or reactive) adaptation (adaptations that occur 'naturally', without interventions by public agencies) and planned adaptation by managers as the result of a deliberate policy decision (IPCC 2001).

In the global context, climate change adaptation research is a relatively new and evolving field. As yet, little is known or understood about the adaptive capacity and sensitivity of many of the values of Australia's World Heritage properties to the impacts of climate change, particularly with respect to some cultural values. However, based on our current level of knowledge and understanding of climate change impacts, it is possible to classify the adaptive capacity of Australia's World Heritage values (using UNESCO's criteria as a proxy) into three broad categories [12]: low, moderate and high. This categorisation is based on a comparative analysis over all World Heritage values. These are summarised in Appendix B.

The natural values listed in UNESCO's criteria (ix) and (x) (i.e. '*… examples representing on-going ecological and biological processes in* [the] *evolution*' and '*… in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation*') have a low level of adaptive capacity to climate change. Because projected rates of climate change are likely to occur faster than the natural rate and frequency of climatic variation, many of the natural values such as our plants and animals will simply not have enough time to adapt. Hence human intervention is crucial to ensure that sustainable adaptive responses are developed and incorporated in management strategies. They therefore require, as a matter of priority, the application of appropriate adaptive management strategies to strengthen their resilience.

A moderate level of adaptive capacity is assigned to those natural values listed under criteria (vii) and (viii) (i.e. geomorphic or physiographic features) and to the cultural values listed under criteria (iii), (iv), (v) and (vi) (i.e. *outstanding example(s) of a traditional human settlement; or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change*).

12 This comparative assessment is based on our current knowledge of climate change impacts on World Heritage values. It should also be noted that the amount of time and research devoted to the effects of climate change on World Heritage values is disproportionate between the natural and cultural values. A broad-scale state-of-the-art vulnerability assessment is required across all properties and values.

Based on this comparative assessment, there would appear to be a greater level of resilience to climate change impacts for cultural values relating to historic built heritage (criteria (i) and (ii)), other than in relation to changes in sea level and chemistry. However, it is important to recognise that our knowledge of climate change impacts on our built heritage is limited or, in some cases, non-existent. Clearly, the assessment used here highlights the need for regular monitoring and reporting of climate change impacts across all properties and values. UNESCO has recommended the use of state-of-the-art vulnerability assessments that could be adopted for all World Heritage sites (UNESCO 2006).

Several actions could be contemplated in the short term to improve the resilience of our World Heritage values to climate change; these are outlined below.

6. KEY FINDINGS AND RECOMMENDATIONS

A paper [13] prepared for the UNESCO Special Expert Meeting of the World Heritage Convention on the Impacts of Climate Change on World Heritage discusses three broad actions that need to be taken to ensure that that the world's unique heritage sites are protected from the effects of climate change. These include:

1. mitigation: reporting and mitigation of climate change effects through environmentally sound choices and decisions at a range of levels—individual, community, institutional and corporate

2. adaptation to the reality of climate change through global and regional strategies and local management plans

3. creating and sharing knowledge including best practices, research, communication, public and political support, education and training, capacity building, networking, etc.

The key findings outlined in this report also reflect some of the actions and recommendations described in UNESCO's report *Predicting and managing the effects of climate change on World Heritage* (UNESCO 2006).

6.1 Opportunities for mitigation

Key finding 1: Explore opportunities for World Heritage properties to contribute to reducing greenhouse gas emissions

The latest IPCC report states that '*global warming is unequivocal*' and is due largely to an increase in greenhouse gases, such as CO_2, caused by burning fossil fuels. Mitigation involves intervention by humans. The IPCC defines mitigation as 'an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases' (IPCC 2001).

Key action

- According to UNESCO, '*the UN Framework Convention on Climate Change is the preferred international tool to address mitigation at the global and States Parties level. However, some mitigation opportunities could be contemplated in the context of the World Heritage Convention at the level of World Heritage sites*', for example, by investigating and quantifying the extent to which World Heritage properties and conservation programs can contribute to the sequestration of carbon (UNESCO 2006).

6.2 Adaptation and management

Key finding 2: Vulnerability assessments and the application of appropriate adaptive strategies

Appropriate adaptive management plans and strategies are needed to minimise the impacts of climate change on World Heritage values.

13 Background paper: *The impacts of climate change on World Heritage properties,* <http://whc.unesco.org/uploads/activities/documents/activity-393-1.doc>

Key actions

- Implement more comprehensive vulnerability assessments for each World Heritage property, as recommended by UNESCO's Expert Committee (see Appendix B for more detail).
- Reduce non-climatic stress factors, such as the spread of invasive species, so as to enhance resilience of Australia's World Heritage properties (particularly the natural values listed under criterion (x)) to climate change impacts. This will require the removal or eradication of introduced pest species and the constant review of access by humans to World Heritage sites.
- Develop ex situ conservation measures or techniques, such as living collections and seed banks, for species at greatest risk from the effects of climate change. An example is those species restricted to the cloud forests of Lord Howe Island Group and the Wet Tropics of Queensland.
- Implement sympathetic management of zones around natural heritage properties and, where necessary, the protection of land suitable for refugia. There is also a need to improve connectivity between reserves to allow species to move freely between habitats.

6.3 Creating and sharing knowledge

Key finding 3: Knowledge management, information sharing and capacity building

Information on potential climate change impacts is continuing to grow steadily. However, there is no universal mechanism allowing policymakers and land managers to coherently assemble and assimilate the vast amount of scientific literature and data to assist with the development of best management practices for the protection of Australia's World Heritage properties. Furthermore, sharing and cross-fertilisation of ideas and knowledge between researchers, managers and policymakers across properties or jurisdictions is lacking. Knowledge sharing and networking across jurisdictions is vital for the development of efficient and effective climate response strategies for Australia's World Heritage properties. It is essential that managers of properties develop a system to report and monitor climate effects on World Heritage values, and that this information be shared among stakeholders and managers alike.

Key actions

- Develop a climate change management plan for Australia's World Heritage properties and their values, with coordinated input from land managers, landowners, state and Commonwealth Government representatives and researchers.
- Create and support networks among researchers—and between researchers and managers—to encourage sharing of knowledge and experience, and monitoring of responses to climate change. This issue requires urgent consideration.
- Undertake capacity building—both human and institutional—in climate change science, policy and management through development of multidisciplinary training programs to improve understanding of climate variability and climate change.

Key finding 4: Collection of baseline biodiversity data (genetic, species, ecosystem)

The study identified that there is a greater need for the collection of baseline data and information about climate change impacts on species and ecosystems, and genetic diversity among species (such as species endemic to particular properties).

Key actions

The data gaps identified above could be addressed by:

- enhancing the collection of baseline data (ecological, species-based, genetic, ecosystem/landscape-scale) and the monitoring of parameters critical for adaptive management. There is a need to clearly identify and assess those values that are likely to be more susceptible to the impacts of climate change, and to further our understanding of the adaptive capacity and resilience of species, communities and ecosystems
- where useful and scientifically supported, identifying and monitoring indicator species to track climate change impacts.

Key finding 5: Support development and use of regional climate change projections, current climate data and palaeoclimatic data relevant to World Heritage properties that are essential for preparedness planning

Reconstruction of past climates—from records captured in caves, coral reefs, ocean sediments, ice cores and trees—is an important component of climate prediction. These past climates, known as palaeoclimates, can be used to place current climate change in context with natural variability, and to calibrate the predictive climate models. However, although some work of this kind is underway, e.g. at Naracoorte (Australian Fossil Mammals Sites), there is a general lack of site-specific palaeoclimatic information to assist our understanding of natural climate variability and climate change for many of Australia's World Heritage properties.

Although global climate models (GCM) are an effective tool to explore future climate change scenarios, many of the models lack resolution at local geographic scales and therefore cannot provide useful local climate scenarios to assist with local management planning.

Key actions

The deficiencies identified above could be addressed by:

- seeking the development and use of fine-scale climate projections/scenarios based on GCMs for Australia's World Heritage properties and their provision in a form that is useful for managers of World Heritage sites to develop adaptation strategies for their properties
- improving the collection of weather and palaeoclimatic data in World Heritage properties to enhance our understanding of climate variability, and to provide for the development of site-specific predictive models.

Key finding 6: Cultural heritage

The study found that the archaeological and cultural heritage literature has concentrated on specific site management issues (e.g. restrictions on access and excavation) and national regulatory regimes (including restraints on trade in movable heritage); however, there is little knowledge or understanding of the potential impacts of climate change on archaeological and other cultural heritage sites, such as the effects of changes in fire regimes and sea level rise.

Key action

The extent of vulnerabilities of archaeological (e.g. Pleistocene and Holocene burial sites) and other cultural heritage sites (e.g. cave paintings) warrants further investigation.

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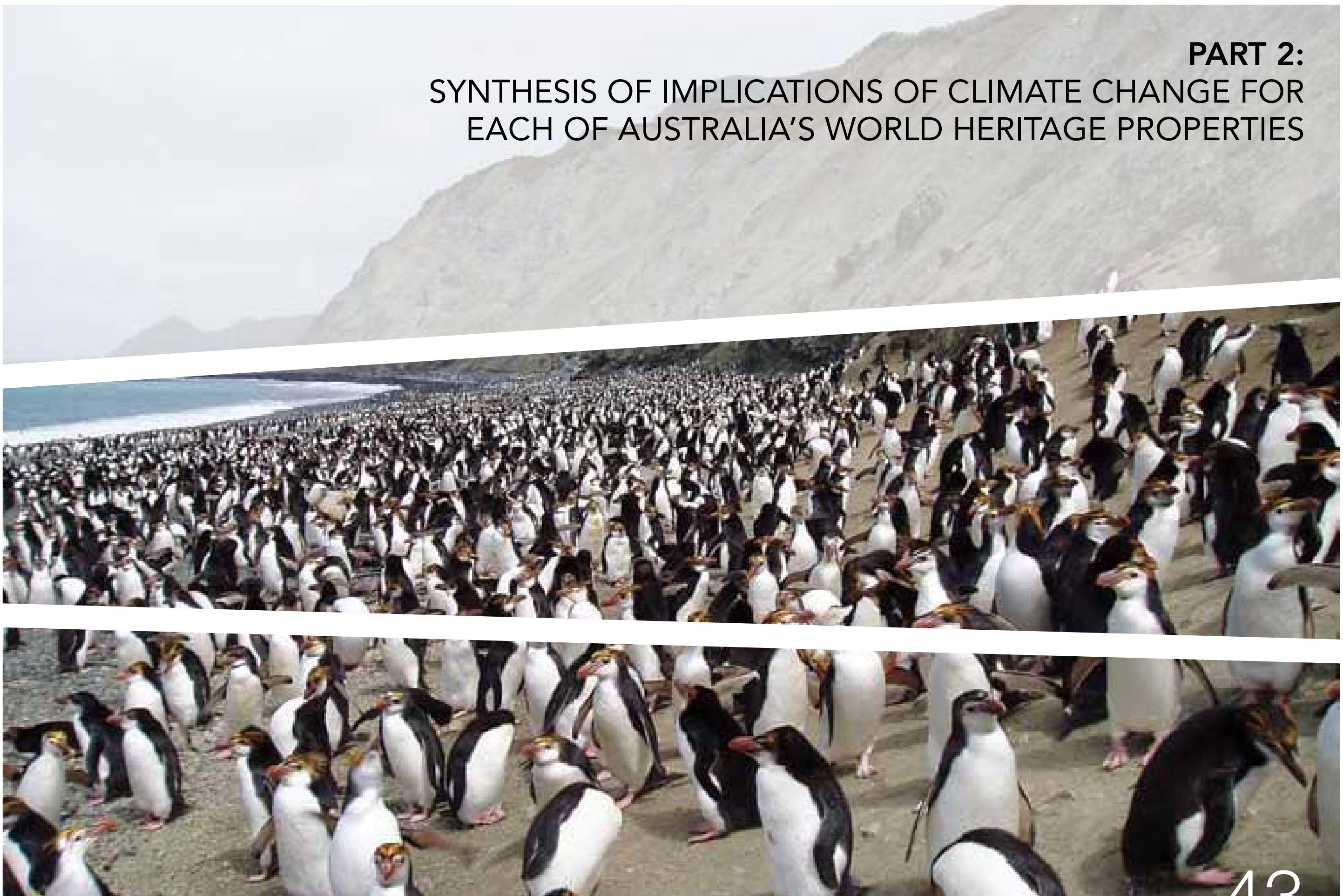
PART 2:
SYNTHESIS OF IMPLICATIONS OF CLIMATE CHANGE FOR EACH OF AUSTRALIA'S WORLD HERITAGE PROPERTIES

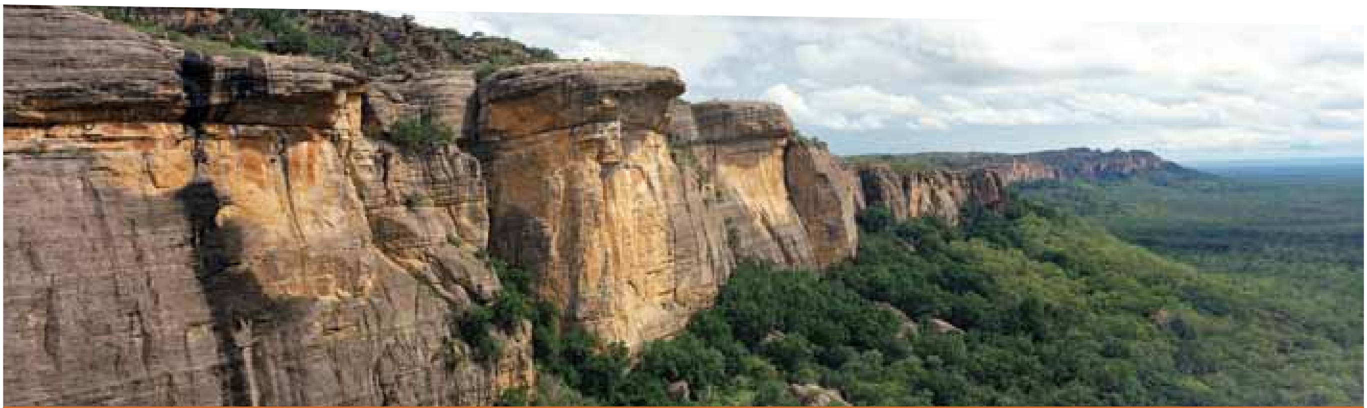


8. CLIMATE CHANGE IMPACTS ON AUSTRALIA'S WORLD HERITAGE PROPERTIES

Organised to reflect date of inscription on the World Heritage List, the following discussion considers the impacts of climate change on each of Australia's World Heritage sites.

Potential impacts are discussed in relation to both the World Heritage criteria for which the property is listed as well as the property's identified values derived from the nomination dossier, technical assessment and the World Heritage Committee's decision to inscribe the site on the World Heritage List. More detailed information on the values of each World Heritage site can be obtained on the DEWHA website <http://www.environment.gov.au/heritage/places/world/index.html>.

8.1 Kakadu National Park



Arnhem Land Escarpment, Kakadu National Park. *Ian Oswald-Jacobs and the Department of the Environment, Water, Heritage and the Arts*

8.1.1 Climate change scenarios for the 'Top End'

The following climate change scenarios, relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[14]

- Average annual temperature is projected to rise by 1.3 °C ± 0.6 °C by 2030.
- Average annual rainfall is expected to remain essentially unchanged (0% ± 7.5%).
- Tropical cyclones are likely to become more intense with a 10% increase in wind speeds.
- Extreme storm events and severe droughts are likely to become more frequent.
- Sea level is expected to rise by an average of 17 cm by 2030.[15]

8.1.2 Summary of impacts

Kakadu National Park (12°40'S, 132°50'E) is located in the tropical savanna of the wet-dry tropic region of Northern Australia. It covers an area of about 20,000 km^2. The park is managed jointly by the traditional Aboriginal owners and the Australian Government Director of National Parks.

- Total rainfall in this region has increased by 50 mm each decade since 1950 (BOM 2006). Annual rainfall may continue to increase but, even if it remains unchanged, evaporation is likely to be higher (CSIRO 2006).
- Although fire is a natural phenomenon in these savanna landscapes, altered fire regimes have emerged as a major threat to some World Heritage values of Kakadu, especially if longer periods of warmer, drier weather occur and especially if invasive grasses spread.

14 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

15 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

- Further increases in atmospheric CO_2 concentrations could also result in an increase in the expansion of woody shrubs into arid and semi-arid regions. However, the potential increase in primary production of vegetation resulting from increased CO_2 availability is probably limited by the poor nutrient status of the savanna soils and may also be limited if water availability becomes reduced through increased evaporation.
- Higher temperatures and more frequent extreme weather events may facilitate the spread and re-emergence of diseases such as malaria, encephalitis, Japanese encephalitis, melioidosis (caused by the bacterium *Burkholderia pseudomallei*) and Kunjin/West Nile virus, which are of major concern to both Indigenous and non-Indigenous communities within Kakadu. The impact of climate change on diseases that affect the fauna is not known.
- The lowland parts of Kakadu are vulnerable to changed salinity as a result of sea level rise and saline intrusion into groundwater. Sea level rise will lead to a further extension of tidal rivers and pose a significant threat to freshwater wetland systems, resulting in conversion of freshwater wetlands to saline mudflats. Up to 80% of freshwater wetlands in Kakadu could be lost, with rises in average temperatures of 2–3 °C.
- Habitats that will be impacted by climate change in Kakadu include freshwater wetlands, mangroves, monsoon forest, riparian communities, beaches and stream hydrology (Bayliss et al. 1997).

8.1.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criteria

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals

Criterion (x): To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Values include:

Coastal riverine and estuarine flood plains including freshwater wetlands, mangrove swamps and beaches.

The Kakadu wetlands were identified by the IPCC to be at risk of significant loss of biodiversity as a result of climate change by 2020.

The Alligator Rivers region of Kakadu experiences marked climatic variation and tidal fluctuations (Eliot et al. 1999), and the region has attracted considerable interest in the likely effects of potential climate change (Bayliss et al. 1997). The park is protected by a natural levee, formed by alluvial deposition, which acts as a partial barrier between freshwater and saltwater systems. In effect, much of the park's freshwater wetland lies in a basin, protected from salt water by the levee. However, in some places the levee is less than 0.5 m in height and the coastal plains of Kakadu as a whole are only about 0.2 to 1.2 m above the high tide mark (Eliot et al. 1999).

The salinity of Kakadu's wetlands was relatively low prior to the 1950s, because the natural levee formed a barrier to saltwater intrusion. However, the presence of large numbers of buffalo in the mid-1970s—together with a combination of higher flood levels and more frequent extreme high tides—resulted in erosion of the levee, with a consequent increase in the salinity of the wetlands as more frequent saltwater intrusion occurred (Cobb et al. 2000).

Sea level is rising faster in northern Australia than elsewhere—up to double the global rate. Since the 1980s, saltwater intrusion into freshwater swamps observed since the 1950s has been accelerating, which may be related to sea level and rainfall changes

(Winn 2006 cited in Hennessy et al. 2007). Projections of sea level rise differ, but current projections are that sea level in Kakadu will rise by at least 17 cm, and perhaps more likely up to 30 cm by 2030 (CSIRO 2006; Eliot et al. 1999; Hennessy et al. 2007).

As sea level rises, as cyclones become more intense and as storm-surge events become more frequent, saltwater intrusion further up rivers and into freshwater wetlands will increase. This is likely to alter the structure and species composition of freshwater plant and animal communities (Muschal 2006) and shift the spatial occurrence of the coastal, estuarine and floodplain ecosystems (Eliot et al. 1999). Hare (2003) projects an 80% loss of freshwater wetlands in Kakadu for a 30 cm sea level rise, which is projected to occur by 2050.

Mangrove communities are extremely sensitive to changes in salinity (Eliot et al. 2000; Ellison & Farnsworth 1997). Surveys carried out in 1998 and 1999 have shown an expansion in the distribution in mangroves in Kakadu over a 41-year period (Lucas et al. 2002). This has been attributed to increases in salinity due to sea level rise, as well as to localised climatic and coastal effects such as tidal scouring (Cobb et al. 2000).

Geomorphological studies of the riverine environment around the South Alligator River reveal that vast areas were dominated by mangrove swamps during the Holocene period around 6,000 years ago when sea level was about 1 m above its current level (Chappell & Grindrod 1985; Eliot et al. 1999; Woodroffe et al. 1986).

In light of geomorphologic history, it is reasonable to suggest that mangrove dominance may reoccur. Clearly, a 1 m sea level rise would significantly increase salinity and result in expansion of mangrove communities along tidal rivers. Clark and Guppy (1988) suggested that a sea level rise of this magnitude would transform present freshwater wetlands into mangrove-dominated swamplands. Eliot et al. (1999) suggested that it would see a return to the extensive mangrove communities that existed 6,000–7,000 years ago. Conversely, formerly widespread species, such as *Melaleuca* spp., would reappear if sea level were to fall again (I White 2006, pers. comm.).

The impact of increasingly frequent severe storm events and cyclones on mangrove communities and wetlands is largely unknown. However, a survey of Louisiana's wetlands following Hurricane Katrina revealed that about 260 km^2 of coastal wetlands were destroyed (Marris 2005). Cyclone Larry in Australia's Wet Tropics caused particularly severe damage in smaller forest patches and riparian vegetation strips on the coastal lowlands (Turton & Dale 2007). Severe cyclones and hurricanes have resulted in extensive destruction of wetland systems in the past but they have regenerated. Mangroves often sustain considerable damage following cyclonic activity but display considerable resilience and resprout readily following catastrophic weather events (Bardsley 1985).

Rising sea level will also contribute to the erosion of coastal regions, as has been reported along the east coast of the United States (Zhang et al. 2004). 'Soft' coastal landforms, such as muddy estuarine and deltaic shorelines, are particularly vulnerable to rising sea levels and severe storm-surge events (Sharples 2006).

High diversity and abundance of plant species, many of which are adapted to low-nutrient conditions. Extensive and relatively unmodified vegetation cover.

Kakadu National Park has an abundance of plant species of conservation significance. These include *Arthrochilus byrnessii*, *Cycas conferta*, *Desmodium* sp. 2, *Eucalyptus koolpinensis*, *Hildegardia australiensis*, *Micraira* spp., *Neobyrnesia suberosa*, *Pityrodia* spp., *Plectrachne aristiglumis* and *Typhonium russell-smithii*. Fire and rainfall are important determinants of vegetation change and distribution (Banfai & Bowman 2005; Bowman et al. 2001a, b; Bowman et al. 2004). Future climate change is therefore likely to have an impact on vegetation growth through changes in rainfall patterns, and fire frequency and intensity.

Increased atmospheric carbon dioxide (CO_2) concentrations are also likely to impact on plant species through a process known as the 'CO_2 fertilisation effect', whereby plant growth is accelerated under high concentrations of CO_2. However, this may be countered by water and nutrient availability. Under laboratory conditions, higher atmospheric CO_2 concentrations will provide greater benefit to woody C3 plants, compared to C4 photosynthetic grasses which are less affected by higher CO_2 concentrations (Bond et al. 2003). Increased CO_2 concentrations could change the competitive nature of plant species. Increases in atmospheric CO_2 concentration may increase the growth rate and subsequent expansion of woody C3 species, which could result in a major shift in the vegetational composition of savanna lands (Johnson et al. 1993). The CO_2 fertilisation effect can also influence a range of physiological processes in plants including water uptake efficiency and nutrient use efficiency (Drake et al. 1997).

Studies of vegetation change in savanna areas have focused on regions outside, but in proximity to, Kakadu. Study of an historical sequence of aerial photographs has shown that a rapid expansion of closed forest vegetation (as opposed to savanna) into areas formerly dominated by grassland occurred over a 50-year period (Brook et al. 2005). Brook et al. (2005) stated '*closed forest expansion occurred most frequently in fire protected sites along forest edges and regression in the more fire-prone areas. Possible drivers for this expansion may include changed fire regimes associated with the cessation of traditional Aboriginal fire management or the "fertilizer" effect caused by the continued increase in global atmospheric* CO_2 *over the course of the* 20^{th} *century. This effect may be changing the competitive balance between C3 trees of the closed forest and the largely C4 tropical grasses of the savanna*'.

However, the expansion of woody plant species does not appear to be a widespread phenomenon in northern Australia. Reduction or loss of woody biomass has been reported in some instances (Sharp & Bowman 2004), and the magnitude and extent of woody vegetation dieback and recovery may be attributable to factors that may not be related to human-induced climate change (e.g. natural climatic variability). Furthermore, access to the growth benefits of increased CO_2 concentrations in savanna regions is likely to be limited by the often poor nutrient status of the soils as well as to changes in water availability (Howden et al. 1999).

Cyclones may become less common, but are expected to become more intense, which may inflict greater physical damage on vegetation, including the uprooting of trees. Trees above 9 m in height are particularly prone to wind damage (Williams & Douglas 1995). A survey of damage following Cyclone Monica in April 2006 revealed that smaller shrubs were able to withstand the highly destructive winds generated by this category 4 cyclone (L Prior 2006, pers. comm.). Any disturbance to the soil can also affect soil dynamics and expose the landscape to greater risk from erosion (D Jones 2006, pers. comm.).

A combination of sea level rise, storm surges, coastal erosion and saltwater intrusion will change the composition of plant communities in wetland communities (Eliot et al. 1999). Increases in saltwater intrusion along stream lines will lead to further expansion of mangrove communities as well as further loss of *Melaleuca* (paperbark) trees, and the coastal mangrove fringe will be reduced in area.

Yellow Water billabong. *John Baker and the Department of the Environment, Water, Heritage and the Arts*

High diversity and abundance of mammal and birds species of conservation significance including species which have experienced range contraction.

The relationship between rainfall variability and fluctuations in mammal populations in arid and semi-arid regions is well documented (Braithwaite & Muller 1997; Dickman et al. 1999; Woinarski et al. 2001). When compared with the temperate zones, the arid and semi-arid regions of Australia have suffered little from land use changes such as agriculture and forestry, but have experienced a higher rate of decline in mammal populations (Woinarski et al. 2001). Population surveys undertaken within a 300 km^2 study area of Kakadu between 1986 and 1993 showed significant declines in some mammal populations (Braithwaite & Muller 1997). It was hypothesised that lower groundwater levels attributed to a succession of wet seasons with lower-than-average rainfall caused the decline. However, a more recent study revealed that while some species had made a good recovery following a period of higher rainfall, many species continued to decline (Woinarski et al. 2001). Woinarski et al. (2001) showed that smaller mammals, such as *Pseudomys* (a rodent genus that includes the delicate mouse (*Pseudomys delicatulus*)), exhibited a greater resilience to these climatic changes. Downward trends in numbers of granivorous birds in northern Australia have been recorded, attributed to declines in habitat suitability associated with changing fire regimes and pastoralism impacts. Declining species in Kakadu include the common bronzewing (*Phaps chaleoptera*), partridge pigeon (*Geophaps smithii*), star finch (*Neochmia ruficauda*), Gouldian finch (*Erythrura gouldiae*), chestnut-breasted mannikin (*Lonchura castaneothorax*) and chestnut-backed buttonquail (*Turnix castanota*) (Fisher & Woinarski 2008). The impact of changing climate for these species is not yet clear.

Climate change will interact with other factors contributing to the decline of mammal populations in Kakadu, including inappropriate fire regimes (Pardon et al. 2003) and introduced exotic plants, animals and diseases (Bradshaw 2008; Short & Smith 1994; Smith & Quin 1996; Walden & Gardener 2008).

More intense fire regimes may occur as a result of hotter dry seasons (particularly hot spells), which may threaten monsoon forest (Bartolo et. al. 2008). Interaction of fire with highly flammable invasive grass species would greatly compound the threat under climate change (Williams et al. in press). Presence of grassy weeds, such as gamba grass, leads to altered fire regimes with more intense and frequent fires that convert savanna woodlands to grassland by destroying trees and shrubs unable to persist under the new fire regime (Walden & Gardener 2008).

Pardon et al. (2003) found that the fire regime had a greater impact on bandicoot survival than factors such as age, gender, rainfall and vegetation type. A similar survey conducted in Litchfield National Park produced a similar result and concluded that an implementation of a sustainable fire management regime was a major priority for park managers (Woinarski et al. 2004).

Many bird species depend on good seasonal rainfall and on fire regimes that favour grass-seed production. For example, annual burning of grasslands will ensure a constant supply of *Oryza* (wild rice), which is an essential source of food for the magpie goose in the Woolwonga wetlands of Kakadu (Lucas & Lucas 1993; Lucas & Russell-Smith 1993). The timing of controlled fires is also a critical factor for some bird species. A late prescribed burn during the dry season, for example, can minimise disruption to ground-nesting birds such as the partridge pigeon, white-throated grass wren (*Amytornis woodwardi*), quails, finches and whistle-ducks (Lucas & Lucas 1993).

Kakadu National Park foreshores and beaches are a major staging point within Australia for many migratory birds including the beach stone curlew, plovers, terns, sandpipers, pied and sooty oyster catchers, eastern curlew and whimbrel; and 35 species of waders, many also migrants, have been recorded on the wetlands. Other birds only found in the estuarine and tidal areas of Kakadu include the chestnut rail (*Eulabeornis castaneoventris*), the collared kingfisher (*Todiramphus chloris*), the broad-billed flycatcher (*Myiagra ruficollis*), the black butcherbird (*Cracticus quoyi*), the mangrove gerygone (*Gerygone levigaster*) and the red-headed honeyeater (*Myzomela erythrocephala*). The great billed heron (*Ardea sumatrana*), large-tailed nightjar (*Caprimulgus macrurus*) and collared kingfisher (*Todiramphus chloris*) are also commonly associated with mangroves and during the wet season egrets, ibises, herons and cormorants nest in large colonies in the mangrove treetops (Kiessling et al. 2008). While the impacts of climate change on Kakadu's coastal and wetland birds are not known, a decline in waterfowl carrying capacity is anticipated as a result of changes to food availability resulting from saltwater incursion as a result of sea level rise. While resilient to climate change, the currently highly abundant magpie goose is considered likely to decline substantially in numbers due to habitat loss as sea level rises, although the inland Barkly wetlands will not be affected by sea level rise and may be a refuge in the future (Traill & Brook in press).

The direct and indirect impacts of climate change on and through invasive species confound assessment of impacts of other factors. Many weed species already present in Kakadu have the potential to cause dramatic changes at the landscape scale including mimosa, para, salvinia and gamba grass (Walden & Gardener 2008). The anticipated increased incidence of extreme events may have a number of significant impacts, e.g. enhancing dispersal of weed seeds during extreme wet season floods possibly into areas where they would not normally reach, and by increasing the stress on native vegetation, increasing their vulnerability to invasion by other species, or by disturbing the ground or removing native vegetation, thus facilitating weed establishment (Walden & Gardener 2008). Extreme events such as floods or cyclones often lead to irruptions of weeds (and sometimes other invasive species such as ants) in the early successional stages after the event. However, while climate change may exacerbate the impact of some species, other species may be disadvantaged, e.g. climate-induced sea level rises may actually reduce the area of habitat suitable for weeds in low-lying coastal floodplain areas (e.g. mimosa, para grass and salvinia) by increasing salinity beyond their tolerance level (Dames & Moore International 1990 cited in Walden & Gardener 2008).

Reptiles such as the pig-nosed turtle, Pacific or olive ridley turtle, green turtle, loggerhead turtle, saltwater crocodile and freshwater crocodile and freshwater fish species.

Environmental effects on phenotypic traits (sex, size, shape, etc.) in amphibians and reptiles are well documented (Shine 1989). The eggs of reptiles and amphibians, for example, depend on correct nest temperatures for sex determination (TSD) and survival. A rise in temperature caused by climate change could have a direct impact on the reproduction and phenotypic determination of similarly susceptible species (Webb et al. 1986). The pig-nose turtle (*Carettochelys insculpta*), for example, is a TSD species, and changes in its environment that affect nest temperature will influence the sex ratio of its offspring (Webb et al. 1986). Incubation temperature can also affect both the rate of embryonic development and the survival time of hatchlings (Webb & Cooper-Preston 1989). Sex determination in both the saltwater and freshwater crocodile (*Crocodylus porosus* and *C. johnstoni* respectively) is also highly dependent on temperature (Webb et al. 1987).

Climate change may affect reptiles in other ways (Araujo et al. 2006; Carey & Alexander 2003). For example, severe flooding events can lead to a high embryonic mortality rate in the pig-nose turtle (Doody et al. 2004), in common with other riverine turtles (Doody 1995; Plummer 1976).

A much greater threat to reptiles could originate from the projected increased destructive force of tropical cyclones. High-intensity cyclones and storm-surge events could threaten nesting habitats, such as beaches and river banks, of many reptiles including marine turtles (C Bradshaw 2006, pers. comm.). Declines in bird and mammal populations could reduce food availability, and so affect the survival rates and population numbers of reptiles (A Britton 2006, pers. comm.). The responses of most reptiles and amphibians to climate change are largely unknown and require further investigation.

Although the Northern Territory has become wetter since 1950, it is expected that in future it will experience more frequent and severe droughts with reduced runoff into rivers (CSIRO 2006). This will change the hydrological regime and water characteristics including temperature and water chemistry. According to CSIRO's climate change projections, higher evaporative demand in association with little change in annual rainfall in the Top End is likely to result in reduced runoff into rivers and streams (CSIRO 2006). A change in fire regime (more frequent/more intense) could result in an increase in acid deposition, leading to subsequent change to the water chemistry for freshwater fish. Acidification of aquatic ecosystems from biomass burning (i.e. production of acid aerosols), acid sulfate soils and acid rain could lead to a decrease in dissolved organic carbon (DOC) concentrations in waterways (Yan et al. 1996). A decline in DOC concentrations, combined with reduced hydrological flows, is likely to have an adverse impact on freshwater fish populations and their food supply. The impact of climate change on freshwater fish species therefore warrants further investigation.

Kakadu's Stone Country. *Ian Oswald-Jacobs and the Department of the Environment, Water, Heritage and the Arts*

Impact on cultural values

Cultural criteria

Criterion (i): To represent a masterpiece of human creative genius.

Criterion (vi): To be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance. (The Committee considers that this criterion should preferably be used in conjunction with other criteria).

Values include:

Active management of the landscapes by Aboriginal people through the use of fire.

The arrival of European settlers had a significant impact on the numbers and distribution of traditional owners throughout the landscape. The resulting disruption of traditional burning practices had important consequences for the abundance and distribution of some mammal species. Traditional owners used a process of selective burning to create habitat mosaics that favoured the survival and maintenance of certain plants and animals (Bowman 1998). Furthermore, the Indigenous people recognised the importance of burning late in the dry season as opposed to the European practice in which burning has been confined always to the early part of the dry season. Recent field studies have shown that the method and timing of burning can dramatically affect the composition of grasses and trees. The traditional Aboriginal fire regime favoured the growth of perennial grasses, such as *Triodia* spp., whereas contemporary European fire methods create an abundance of highly flammable annual grass species such as *Sorghum* spp. (Russell-Smith et al. 1998, 2003).

Fire management in Kakadu now involves traditional owners in all stages of fire planning, execution and monitoring, and it is now very much influenced by traditional burning practices. While ongoing monitoring in the park has shown that past fire management has not been optimal for some species and communities, this information has contributed significantly to improved fire management practices.

Aboriginal archaeological remains and rock art. Cultural sites including archaeological sites.

Water is the primary agent of rock art deterioration (Pearson 1978; Pearson & Swartz 1991). Rainwater flowing over rock surfaces can result in extensive rock art damage, and groundwater containing salts can percolate through the rock-clay matrix, leading to the formation of silica crusts. Atmospheric conditions, rock moisture and pH determine the extent and depth of rock crust formation (Rosenfeld 1985). Moisture or condensation generated from thick vegetation at the base of rock shelters, as well as extreme and intense fire events, also contribute to the deterioration of rock art (Pearson 1978). During the dry season, wildfires create large quantities of smoke, dust and black ash that contaminate the atmosphere and result in the formation of highly acidic rain during tropical storms. The organic and inorganic acids in rainwater react with rock surfaces to produce small quantities of oxalate-rich salts (Watchman 1991). Extreme fire events also lead to rock flaking and soot accumulation.

There has been little research specifically examining the impacts of climate change on rock art. However, some conclusions can be drawn about the effect of climate change on the persistence of rock art, based on what is already known about the effect of weathering on rock art. Historically, extensive flooding has had a devastating impact on rock art and archaeological sites (Rosenfeld 1985). Rock art values could be at risk from an increase in extreme storm events in the future. Access to sacred sites could also become severely restricted by sea level rise (J Morrison 2006, pers. comm.).

Access to all sacred sites in the Northern Territory is regulated by legislation, and in Kakadu public access to sacred sites is restricted and highly regulated. Only three of the many thousands of rock art sites are available for viewing by the general public. The main management problem arising from climate change is likely to be prioritising site maintenance based on the likelihood of exposure of sites to more frequent and more intense weather events.

The techniques used to conserve rock art include the use of silicone-based compounds and silicone drip lines to divert water away from rock art surfaces. In some cases, the pigments in the artwork have been treated with low concentrations of impregnated silicone (Pearson 1978). The removal of vegetation ensures better ventilation and less condensation, but can also result in higher moisture evaporation from rock surfaces and subsequent acceleration of salt crystallisation (Rosenfeld 1985). In addition, hydration of the clay-rock matrix can result in granular disintegration and flaking (Rosenfeld 1985). An understanding of the nature of the pigments, the rock surfaces on which they occur, and how they react under a range of environmental conditions, is a major component of a rock art conservation management strategy (Ford et al. 1994).

The World Heritage values for Kakadu include archaeological sites such as mounds, stone flaking areas and middens, as well as its wetlands. These values could be destroyed by rising sea levels.

8.1.4 Associated threats

The abundance and distribution of weed species, in particular, will be very much influenced by climate change. Weeds will continue to be a major threat to some of Kakadu's World Heritage values, and will be a focus for management authorities. The giant sensitive plant (*Mimosa pigra*), salvinia (*Salvinia molesta*), mission grass (*Pennisetum polystachion*), gamba grass (*Andropogon gayanus*) and olive hymenachne (*Hymenachne amplexicaulis*) all pose significant threats to the integrity of Kakadu's World Heritage values. The spread of the cane toad (*Bufo marinus*) into the wetlands of Kakadu is also of major concern to stakeholders and managers, but its response to climate change is unknown.

Changes in disease occurrence in relation to native fauna with climate change is not known, although the impact of disease on the human population is of major concern and an issue affecting both Indigenous and non-Indigenous communities, and may affect visitors. It is expected that many diseases including malaria, encephalitis, Japanese encephalitis and melioidosis will have the potential to spread more widely as a result of global warming. Melioidosis is a major health problem in the Northern Territory, and its incidence is closely linked to intense rainfall and cyclonic activity (B Currie 2006, pers. comm.). The impact of climate change on the chance of pathogens carried by feral animals, such as Japanese encephalitus and bovine tuberculosis, becoming established in Australian feral animal populations is not known.

8.1.5 Gaps in knowledge and future directions

In the context of climate change, the following issues need to be addressed to ensure the future conservation of Kakadu National Park and its values:

- Better communication and education strategies are needed.
- Access to information, such as scientific reports, is extremely poor. The availability and dissemination of electronic information is reported by stakeholders and researchers to be 'piecemeal' and 'poorly catalogued'. A significant improvement is required with effective use of modern communications technology, such as a web-based information portal.

- The vulnerability of freshwater wetlands to further saline intrusion is unknown and additional research into this is urgently required.
- Further research is needed to determine the geomorphologic processes and mechanisms associated with saline intrusion. There is scant information on plant species' adaptation to the floodplain environment (Finlayson 2005). Consequently, there is a need for better understanding of the biological interactions and associations at the tidal–freshwater interface.
- Ongoing recording of saltflat expansion using remote sensing and geographic information systems is required.
- The response of vegetation to environmental change is still largely unknown. An integral part of a management strategy is the ability to predict future changes in vegetation patterns. Improved knowledge of plant growth and the environmental factors that drive seasonal and annual changes in vegetation distribution and productivity is required to enable managers to control invasive species and modify fire regimes appropriately (Finlayson 2005). Very little is known about the impact of rising atmospheric CO_2 concentrations. The relationship between CO_2, and the expansion of woody vegetation and nutrient availability, requires further investigation.
- The impacts of future climate change on rock art are poorly understood and research is urgently needed. The impacts of climate change on other kinds of cultural sites found in Kakadu also need to be researched further.
- Changing pathogen and disease dynamics associated with climate change are of concern for fauna, and for human residents and visitors. Ongoing monitoring and modelling of disease responses are essential for early detection.

8.2 Great Barrier Reef

One Tree Island Reef in the Capricorn Bunker group. *J. Oliver GBRMPA*

8.2.1 Climate change scenarios for north-east Queensland

The following climate change scenarios for north-east Queensland, relative to 1990 (CSIRO & BOM 2007), are based on a 'high' greenhouse gas emissions scenario.[16] However, the reef extends over 2,600 km from north to south, and southern projections may be more similar to those of the northern parts of the Gondwana Rainforests of Australia.

- The average annual air temperature for this World Heritage property is expected to increase by 1.3 °C ± 0.6 °C by 2030.
- Annual average rainfall is likely to fall by 3.5% ± 11% by 2030, although changes are likely to be seasonally variable, with drier autumns and slightly wetter summers.
- There is likely to be a decrease in annual runoff into rivers, resulting from higher evaporative demand and a decrease in annual rainfall, which may reduce flows into the ocean.
- Severity of storms and cyclones is likely to increase.
- Changes to the ENSO are expected but it is still unclear how the frequency and intensity of El Niño events will change as a result of global warming (IPCC 2007).
- Sea level is expected to rise by 17 cm by 2030.[17]
- Sea water is expected to become warmer (temperature is expected to increase by 0.7 °C to 0.8 °C by 2030 (Johnson & Marshall 2007)) and more acidic; pH is likely to decline (by 0.2 units by 2070 (Hobday et al. 2006)).
- The severity and frequency of drought is expected to increase.

Projections for the Great Barrier Reef are discussed in more detail in Johnson and Marshall (2007).

8.2.2 Summary of impacts

The Great Barrier Reef extends from the northern extremity of Cape York Peninsula to southern Queensland (10°40'55"S, 145°00'04"E to 24°29'54"S, 154°00'04"E). About 99.3% of the World Heritage property is within the Great Barrier Reef Marine Park, with the remainder in Queensland waters and islands. The Great Barrier Reef is internationally renowned, containing unparalleled biological diversity as summarised in Table 4. Its significant natural values are internationally recognised through its inclusion on the World Heritage List. Its network of reefs—about 2,900 in total—is the largest and most complex coral reef system in the world, making it a critical global resource.

Within the World Heritage site, 70 broad habitat types (bioregions) have been identified ranging from fringing coral reefs, mangroves and seagrass meadows, to algal and sponge gardens, sandy or muddy benthic communities and mid-shelf reefs, and then to the exposed outer reefs and deep oceanic features (Fernandes et al. 2005). Within the outer boundaries there are also over 900 islands.

16 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

17 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

Table 4. Summary of significant features of the Great Barrier Reef (Source: Great Barrier Marine Park Authority, pers. comm.)

Six of the world's seven species of marine turtle	The largest green turtle breeding area in the world
One of the world's most important dugong populations	Over 43,000 km^2 (estimated) of seagrass meadows
A breeding area for humpback and other whale species	Over 2,900 coral reefs built from over 360 species of hard coral
More than 1,500 species of fish	1,500 species of sponges equalling 30% of Australia's diversity in sponges
2,200 species of native plants which is 25% of Queensland's total native plant species	800 species of echinoderms (e.g. sea stars) = 13% of the world's total species
Over 5,000 species of molluscs	Over one-third of all the world's soft coral and sea pen species (80 species)
Over 175 species of birds	Approximately 500 species of seaweeds
Over 2,000 km^2 of mangroves including 54% of the world's mangrove diversity	Spectacular seascapes and landscapes, e.g. Hinchinbrook Island, the Whitsundays
Extensive diversity of reef morphologies and geomorphic processes	Complex cross-shelf and longshore connectivity

Climate change impacts are already being observed in the Great Barrier Reef. Average annual rainfall has already declined over the past century and rainfall intensity has increased. The Great Barrier Reef ecosystem is highly vulnerable to climate change and impacts are already being observed on plants, animals and habitats; for example, coral bleaching events are occurring more frequently and consequential changes to the biodiversity are being observed.

Management of the Great Barrier Reef involves a number of agencies; the Great Barrier Reef Marine Park Authority (GBRMPA) is the primary adviser to the Australian Government for the care and development of the Marine Park and World Heritage property. Many other Commonwealth and Queensland agencies are also involved in management, with Queensland Parks & Wildlife being a major provider of day-to-day management activities in the Great Barrier Reef (including the islands, many of which are national parks). Many other stakeholders including research institutions, commercial and recreational fishing bodies, tourism associations and industry, Indigenous traditional owners, and community members are also involved in different aspects of management.

The property provides a benchmark for consideration of potential climate change impacts on tropical marine areas in Australia, as it has been the subject of a large number of detailed and specific reports on such impacts. A major collaborative program to implement the Great Barrier Reef Climate Change Action Plan is underway in the region, which aims to increase knowledge about the implications of climate change for the Great Barrier Reef's social and ecological systems, and to develop and support strategies to minimise impacts through improving and maintaining resilience.

The following account accordingly offers only a brief summary of key issues. Readers are referred for more information to the major reports and salient research papers (see reference list for details). Key documents include:

- *Climate change and the Great Barrier Reef: A vulnerability assessment* (Johnson & Marshall 2007). Published by the Great Barrier Reef Marine Park Authority
- *A reef manager's guide to coral bleaching* (Marshall & Schuttenberg 2006). Published by the Great Barrier Reef Marine Park Authority, National Oceanic and Atmospheric Administration, and International Union for the Conservation of Nature
- *Climate change in the Cairns and Great Barrier Reef region: Scope and focus for an integrated assessment* (Crimp et al. 2004). Published by the Australian Greenhouse Office, Canberra
- *Global climate change and coral bleaching on the Great Barrier Reef: Final report to the State of Queensland Greenhouse Taskforce through the Department of Natural Resources and Mines* (Done et al. 2003)
- papers on thermal bleaching thresholds (Berkelmans 2002; Berkelmans & Willis 1999) and ecological criteria (Done 1995).

8.2.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criteria

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Values include:

> Some of the most spectacular scenery on earth and abundant diverse flora and fauna, such as breeding colonies of sea birds, migrating whales, dolphins, dugongs and congregations of large fish.

The World Heritage values do not explicitly recognise economic, social or cultural concerns. However, it is clear that there is potential for significant damage to the attributes of some parts of the property through climate change, with a consequent effect on industries and communities that depend on the reef, and the regional and national economies. Overall, although landforms are likely to remain substantially intact (with the exception of possible impacts from ocean acidification) degradation of 'natural beauty' may reflect increased frequency and severity of severe wind events such as cyclones, changes in fish populations including species composition, increased infestations of crown-of-thorns starfish, erosion of some littorals and coral bleaching.

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Values include:

> Coral reefs, cays, islands, dunes, serpentine rocks, undisturbed tidal sediments, and distribution of continental island flora and fauna as a record of sea level changes.

Some of the elements that contribute to this value—the process of recording sea level changes and the complete history of the reef's evolution in the reef structure, the record of climate history, environmental conditions and processes extending back over several hundred years contained within old massive corals, and the reflection of the record of sea level changes in the distribution of continental island flora and fauna—will likely be preserved despite the changes that climate change may bring, although there may be some degradation due to acification. However, the vulnerability to climate change of other elements—such as evidence of earlier history, formations such as the serpentine rocks of South Percy Island, intact and active dune systems, and undisturbed tidal sediments and 'blue holes'—is not known.

Heterogeneity and interconnectivity of the reef assemblage; ongoing processes of accretion and erosion of coral reefs, sand banks and coral cays, river deltas and estuaries.

The integrity of the World Heritage property is likely to be substantially impacted by climate change, with regression and erosion of features such as reefs and sediments, and loss of diversity in flora and fauna.

Estimates of sea surface temperature increases in the region during the next 50 years range from a 1.5 °C rise to over 4.5 °C (Done et al. 2003; Johnson & Marshall 2007). Coral bleaching is the major temperature-related impact of concern. Coral reef creation and maintenance is based on the symbiotic relationship between the coral animal and microscopic algae living in the coral tissue. An impairment of algal photosynthesis and loss of algal symbionts has been observed in corals following exposure to many stressors, including thermal extremes (heat or cold), poisons, elevated light and reduced salinity. The increased sea surface temperatures associated with climate change afford the greatest risk to increased incidence of bleaching events, but this can be exacerbated by climate change impacts on other factors, e.g. increased incidence of heavy rainfall events associated with cyclones reducing salinity (Kerswell & Jones 2003) and increased seawater acidification.

Projections of future water temperatures suggest coral bleaching could become an annual event in the course of this century, with suggestions that 'catastrophic' exposure of selected reefs to climate change impacts will be evident by 2050 (Done et al. 2003). The Great Barrier Reef has not yet suffered extensive damage due to coral bleaching. However, approximately 5% of reefs in the Great Barrier Reef were severely damaged in each of the 1998 and 2002 mass coral bleaching events. That is of particular concern given the vulnerability of wider ecosystems and uncertainties regarding adaptation (Done et al. 2003; Hoegh-Guldberg 1999; Hoegh-Guldberg & Hoegh-Guldberg 2004; Johnson & Marshall 2007). See Box 5.

Apart from coral bleaching, an increase in ocean acidification is a major concern for the conservation of the coral reef system in the Great Barrier Reef. Acidification takes place via the reaction of dissolved CO_2 with water to produce carbonic acid which, in turn, lowers pH. The resulting acidification could have a profound effect on calcifying organisms, such as corals, shellfish and some species of phytoplankton, producing calcium carbonate shells (Feely et al. 2004). The carbonate saturation state of sea water decreases with water depth and latitude (Brown 1997; The Royal Society 2005). Increasing acidity will result in slower growth rates of calcifying species, resulting in potentially weaker skeletons. At some point, net erosion will exceed net accretion and reefs will begin to break down (Hoegh-Guldberg et al. 2007).

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Values include:

Diversity of flora and fauna including macroalgae, Tunicata, Crustacea, Mollusca, fishes, seabirds, marine reptiles and mammals, terrestrial invertebrates and vertebrates, feeding and/or breeding grounds for international migratory seabirds, cetaceans and sea turtles.

The Great Barrier Reef hosts a range of infinitely complex ecosystems in which a myriad of species of fish and aquatic vegetation are interlocked in a mutually profitable interdependence. Coral reef systems are naturally very dynamic, undergoing constant change and disturbances; under natural conditions, they have considerable capacity to recover or maintain key processes and functions in the face of disturbances or pressures (Johnson & Marshall 2007). The complexity and interdependence of particular ecosystems makes sweeping assessments of overall impacts not overly useful. However, under climate change it is clear that there is substantial potential for adverse impacts involving disruption of food chains, changes to connectivity, loss of biodiversity, increased susceptibility to disease and weakening of structures such as reefs, seagrass meadows and mangrove littoral systems. The scale of those impacts is likely to vary markedly from location to location, depending on the nature of the bioregion and different topographies (Crimp et al. 2004), and the other human pressures in the area.

Box 5. Coral vulnerability and thresholds

Projections indicate that 500 parts per million (ppm) is the highest CO_2 concentration under which communities of corals can survive as we know them today. Above this concentration, coral reefs will undergo major changes that may be irreversible, leading to degradation that may persist for hundreds or thousands of years. At 500 ppm CO_2, the increases in ocean temperature and acidity are expected to cause coral calcification to decrease to 40% of today's value and major bleaching events (such as occurred in 1998) to occur every two to four years. Under these conditions, Australian reefs will have the following characteristics:

- There will be a major increase in the frequency and intensity of coral bleaching, mortality events and recruitment failure with increased incidences and outbreaks of coral disease.
- Coral-dominated reefs will contract to less that 20% of today's distribution and corals will be rare on most coral reefs. Benthic microalgae, macroalgae and cyanobacteria communities will dominate these reefs, although it is uncertain which species or taxa will dominate.
- Reef carbonate frameworks are likely to disintegrate slowly under vastly reduced calcification (due to elevated temperatures and decreasing pH) and the possible acceleration of bioerosion. Reefs will have less structure and hence reduced habitat complexity and holding capacity for reef organisms. It is not known how long these processes will take to have an effect on coral reefs.
- Reduced coral communities and reef structure will lead to a major reduction in reef biodiversity with some coral-dependent species becoming extinct.
- At longer timeframes, negative reef maintenance and growth will mean that sections of the Australian coastline that are currently protected by reef structures like the Great Barrier Reef will gradually become more exposed to ocean wave stress. This may eventually have ramifications for the current distribution of coastal seagrass and mangrove communities.
- An intensified cyclone regime will increase physical impacts on coral communities and will accelerate the shift from high-diversity communities to assemblages dominated by few resistant massive/encrusting species. Reduced vitality of corals will mean that recovery will be compromised, further accelerating the shift of reefs away from coral dominated reefs.
- The increased intensity of flood events along with prolonged drought along eastern Australia will lead to periods of reduced water quality and flooding (with associated sediment, nutrients, and freshwater impacts) that will affect reefs further offshore.

Source: Hoegh-Guldberg et al. (p. 296) in Johnson and Marshall (2007).

Climate change will impact on community composition and configuration—both change in presence/absence and relative/absolute abundance (evenness/richness) of species present—and novel species assemblages will form. Ecosystem functioning, services and states will see changes such as changes in phenology (the timing of events such as coral spawning events); in nutrient cycling and natural resource supply (e.g. fish and shellfish); in predator–prey, parasite–host, plant–pollinator and plant-disperser relationships; and in ecosystem services such as buffering shorelines from wave action and erosion. Ecosystem switches (e.g. from coral reef to an algal-dominated state) may follow changes in ecosystem functioning and disturbance regimes.

The resilience of the Great Barrier Reef ecosystems to disturbance, like others, is underpinned by the level of redundancy and response diversity present. Redundancy describes the capacity of one species to functionally compensate for the loss of another and response diversity describes the variability of responses within functional groups to disturbance. Some species that seem unimportant may become critical for reorganisation when conditions change, whether slowly (e.g. increasing seawater temperature, changing salinity) or abruptly (e.g. crown-of-thorns or disease outbreaks, cyclones, bleaching events). A wide range of responses enables some species to compensate for others, which facilitates regeneration after a disturbance (Johnson & Marshall 2007).

The capacity of reefs within the Great Barrier Reef to absorb and recover from disturbances relies on a range of factors (Johnson & Marshall 2007):

- the population condition and dynamics of corals, as the major contributors to reef construction
- the balance between corals and benthic algae (algae may pre-empt space, inhibiting or preventing coral recruitment, after coral bleaching episodes)
- level of biological diversity present—marine ecosystems with high biological diversity will generally be relatively resilient, largely because they will have more diverse responses and capacities available to them, which can provide the basis for adaptation to new threats such as climate change
- the extent of the connections between reefs and source populations of the supply of larvae or propagules available to reseed populations of key organisms, such as fish and corals, or to facilitate exchange of genetic material. Connectivity can also reduce resilience, if it facilitates dispersal of undesirable factors, such as disturbance, pollutants (e.g. nutrients) or organisms (e.g. diseases, algae, exotic species)
- presence of refugia help to maintain diversity and abundance by serving as sources for replenishing disturbed populations, and to serve as stepping stones for maintaining connectivity across larger scales
- quality of the chemical and physical environment; a poor-quality environment exacts significant costs to organisms in maintaining physiological health and integrity and in maintaining ecosystem function. A major impact of poor water quality lies in the inhibition of recovery from other stresses and disturbances
- environmental, ecological and physiological factors that relate directly to climate change-specific threats that act in synergy, including thermal protection (ability to avoid or be protected from the oceanographic conditions that induce coral bleaching), thermal resistance and bleaching tolerance.

Criterion (x): To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Values include:

Habitats for species of conservation significance including over 2,900 coral reefs; 600 continental islands supporting 2,195 plant species; over 2,070km^2 of mangroves; and 300 coral cays and sand cays.

It is well documented that the environment can influence phenotypic traits (sex, size, shape, etc.) in amphibians and reptiles (Shine 1989). The eggs of reptiles and amphibians depend on the correct nest temperatures for sex determination and survival, and therefore the impact of climate change can have a direct bearing on reproduction and phenotypic determination. An increase in temperature is likely to lead to changes in gender ratios in reptiles, including the sea turtle species that inhabit the Great Barrier Reef, resulting in a higher proportion of females (Doody et al. 2004; Vogt & Bull 1984). In addition, the range and latitudinal distribution of loggerhead turtles (*Caretta caretta*) is influenced by a range of environmental factors including a rapid change in water temperature and strong currents (Hays & Marsh 1997). There has been a 70–90% decline in loggerhead turtle numbers in the past 30 years.

Dugong populations have also experienced a more than 90% decline in population numbers since the 1960s (GBRMPA 2002). These declines have been attributed to habitat loss or degradation and intensive fishing activities. These marine species may face further population declines from the effects of climate change.

An increase in sea level is likely to affect mangrove distribution and extent, and suitable nesting sites for a range of marine turtle species, with potential for the complete inundation/disappearance of many low-elevation sand cays. An additional threat to marine turtle populations could originate from the destructive force of tropical cyclones and storm-surge events that may threaten nesting habitats of marine turtles. Changes to incubation temperature could affect gender ratios, and changes to circulation patterns can also lead to increased mortality in marine turtle and other species (Roberts et al. 2002), and disruption of hatchling dispersal and migratory cues (Limpus 2006).

Great Barrier Reef coral. *Jeff Maynard*

Studies conducted in North America showed a 90% decline in the population of sooty shearwaters (*Puffinus griseus*) associated with an increase in seawater temperature (Veit et al. 1996). In recent years, seabird populations on the Great Barrier Reef have also been affected by changes in sea surface temperatures. During 2002, wedge-tailed shearwaters (*Puffinus pacificus*) in the southern Great Barrier Reef experienced mass mortality as a result of a rise in sea surface temperature (Smithers et al. 2002).

8.2.4 Associated threats

- Changes to rainfall patterns and increased flooding may result, affecting flora and fauna (e.g. inshore seagrass and corals) on reefs, islands and in estuaries (Bridgewater & Cresswell 1999; Bunt et al. 1982).
- The interaction between climate change impacts and the impacts of land-based activities and coastal development on water quality (through increased sedimentation and nutrient loading) is not known.
- There is threat to a range of marine species from disease. An increase in the frequency of new disease outbreaks and epidemics has been reported (Harvell et al. 2002).
- An increase in visitation and use may exacerbate future climate change effects (e.g. disturbance of seabirds nesting on beaches, which further stresses birds that are already suffering some provisioning failure due to increased sea temperature impacts on food availability).

8.2.5 Gaps in knowledge and future directions

There are numerous issues that need to be addressed in respect of climate change and the Great Barrier Reef. Gaps and recommended future directions are summarised below.

- Sub-regional climate projections for use in understanding location specific impacts are needed, as are more certain cyclone, rainfall and ENSO projections for the Great Barrier Reef.
- Information on the interactions between climate stressors and other stressors such as poor water quality, disease and human uses is required.
- The impact of an increase in sea level and its long-term effect on species habitats (e.g. seabirds and marine turtles) is unknown.
- There needs to be greater understanding of factors that confer resilience on reef ecosystems, and species-specific responses to climate changes, e.g. patterns of coral bleaching and implications for reef systems (Done 1999; Great Barrier Reef Marine Park Authority 2006).
- More research on interactions between coral and algae is needed. This factor is important in understanding susceptibility of coral reefs to climate change and recovery after disturbance (e.g. bleaching or cyclone).
- Changes in ocean temperatures and productivity may be a contributing factor that leads to the decline of seabird populations and other higher trophic species. The relationship between changes in circulation patterns and 'provisioning failure' among seabird populations requires greater understanding.
- The long-term impact of climate change on marine species is largely unknown—marine species (e.g. dugongs, inshore dolphins and marine turtles) may face further declines in population from the effects of climate change.
- Potential climate change impacts on disease and pest population dynamics requires further investigation.
- Government ability to implement adaptive management and address cumulative impacts is uncertain.

Table 5. Predicted impacts of climate change on the outstanding universal value of the Great Barrier Reef (Source: Great Barrier Reef Marine Park Authority, pers. comm.)

This table provides a summary of current knowledge about the vulnerability of key values of the Great Barrier Reef to climate change. The information is extracted from the publication *Climate change and the Great Barrier Reef: A vulnerability assessment*. Coral reefs worldwide are predicted to undergo substantial change as a result of climate change. Although clearly vulnerable to climate change, the Great Barrier Reef is likely to be more resilient than most other coral reef systems on the planet. Therefore, the impacts outlined in the table below are likely to be significantly more severe, or to occur sooner, in most other reef systems in the world.

Vulnerability – High Moderate Low   Certainty – High Moderate Low   Timeframes – years decades centuries

Criteria	Examples of values/attributes	Vulnerability to climate change; nature of impacts	Certainty	Timeframe
(vii) – exceptional natural beauty & aesthetic importance	Spectacular seascapes and landscapes, e.g. Whitehaven Beach, the Whitsunday Islands, Hinchinbrook Island, mosaic patterns of reefs	Beaches are moderately vulnerable: subject to changed locations and profiles and increased loss of sand (sea level rise and increased severity of storms).	Moderate certainty	decades
		Major terrestrial features (high islands, etc.) have low vulnerability.	Moderate certainty	decades–centuries
		Mosaic patterns of reefs are highly vulnerable due to shift to net erosion of reef structures (increased sea temperatures and ocean acidification).	Moderate–high certainty	decades–centuries
	Spectacular coral assemblages (hard and soft corals)	Spectacular coral assemblages have high vulnerability: abundance and local diversity of corals predicted to decline (increased sea temperatures), with a shift toward dominance by organisms such as seaweeds (increased sea temperatures; increased delivery/availability of nutrients).	High certainty	years–decades
	>1,500 species of fish providing a myriad of colours, shapes and sizes	Fish diversity has moderate vulnerability: species of fish dependent on corals (approx. 10% of species) are predicted to decline in abundance, with aesthetic implications as many of the fish providing colour, diversity of shape and size are coral-dependent species.	Moderate certainty	years–decades
		Fish species assemblages are moderately vulnerable: all reef-dependent species are predicted to be affected as a result of loss of habitat (increased sea temperatures).	Moderate certainty	years–decades

Criteria	Examples of values/attributes	Vulnerability to climate change; nature of impacts	Certainty	Timeframe
(viii) – significant geomorphic or physiographic features	The world's largest coral reef ecosystem, extending over 14° of latitudinal range	Size of ecosystem has low vulnerability.	High certainty	
	About 3,000 separate coral reefs, ranging from inshore fringing reefs to mid shelf, exposed outer reefs and deep water reefs and shoals	Number and location of reefs have low vulnerability.	Moderate–high certainty	
	Deepwater features of the adjoining continental shelf including canyons, channels and passes, plateaux and slopes	Deepwater features have low vulnerability.	Moderate–high certainty	
(ix) – significant on-going ecological and biological processes	An extensive diversity of reef morphologies and on-going geomorphic processes	Diversity of reef morphologies has low vulnerability: sensitive morphologies may not be maintained or may be subject to erosion (increased sea temperatures; ocean acidification).	Moderate certainty	decades–centuries
	~ 900 islands ranging from small coral cays (in various stages of geomorphic development) to large continental islands	Ongoing geomorphic processes have high vulnerability: reef-building processes expected to be compromised with net erosion rates (ocean acidification).	Moderate certainty	decades
	Complex cross-shelf, longshore and vertical connectivity facilitated by dynamic current flows, incorporating important ecological processes such as larval dispersal	Patterns of connectivity have moderate vulnerability; changed ocean currents, including upwelling; altered nutrient and larval dispersal (sea temperatures).	Low–moderate certainty	
	Breeding and spawning grounds for unique coral reef associated species, including threatened and vulnerable species such as turtles, whales and humphead Maori wrasse	Breeding and spawning grounds associated with reef habitat have high vulnerability (see vii above).	High certainty	

Criteria	Examples of values/attributes	Vulnerability to climate change; nature of impacts	Certainty	Timeframe
(x) – significant natural habitat for in-situ conservation of biological diversity	Over 2,000 km² of mangroves including 54% of the world's mangrove diversity	Mangroves have moderate to high vulnerability: decreased area (sea level rise and increased storms). (Mangroves may have lower vulnerability if sediment accretion can keep pace with sea level rise; there are no barriers to landward migration and there is sufficient rainfall)	Moderate certainty	decades
	~ 43,000 km² of seagrass meadows, in both shallow and deepwater areas	Seagrasses have moderate vulnerability (increased UV light and sea temperature). (Seagrasses could increase in area due to increased availability of nutrients, if exposure to increased UV light, temperature and storms do not affect growth).	Low certainty	decades
	70 'bioregions' (broad-scale habitats) have been identified comprising 30 reef bioregions and 40 non-reefal bioregions; these include algal and sponge 'gardens', sandy and muddy bottom communities, and continental slopes and deep ocean troughs	Number and location of bioregions has low vulnerability.	Moderate certainty	
	The location of the world's largest green turtle breeding aggregation, regionally important seabird nesting islands, black marlin spawning ground and a significant area for humpback whale calving and rearing	Turtle and seabird nesting is highly vulnerable: loss of nesting habitat, altered sex ratios, reduced survivorship of young (increased air temperature and sea level rise).	High certainty	years–decades

8.3 Willandra Lakes Region

Shifting sands, Lake Mungo lunette. *Mark Mohell and the Department of the Environment, Water, Heritage and the Arts*

8.3.1 Climate change scenarios for Willandra Lakes Region

This region occurs in south-western New South Wales, but its climate trends are expected to be similar to those of inland Victoria, where a hotter (average annual +1.3 °C ± 0.4 °C), drier (3.5% ± 11% decrease in annual rainfall) climate, with increasingly severe drought and a higher evaporative demand (+5% ± 2.5%) is expected by 2030.

8.3.2 Summary of impacts

The Willandra Lakes Region (34°18'S, 143°46'E) is located in the semi-arid south-west of New South Wales. It covers an area of 240,000 ha, of which Mungo National Park comprises about 27,800 ha. Management of the World Heritage site involves state government agencies (in particular NSW National Parks & Wildlife Service), pastoral property owners and Indigenous community representatives.

The landscape of the Willandra Lakes Region comprises a system of shallow channels and interconnected, dry lake basins formed during the Pleistocene epoch. The vegetation in this region is very sparse, consisting of extensive saltbush *(Atriplex stipulata) and* stunted bluebush *(Maireana sedifolia, M. pyramidata).* The vegetation helps maintain the stability of the dunes during extreme weather events and, in earlier times, mitigated the effects of pastoral activity, and grazing by feral animals such as goats and rabbits.

The region formerly enjoyed substantially higher rainfall and access to water via Willandra Billabong Creek, which is reflected in extensive archaeological material originating over the past 50,000 years.

Regrowth of key flora, especially chenopod species such as *M. sedifolia*, after wildfires and grazing may be inhibited by higher temperatures and drought (Graetz & Wilson 1984; Landsberg et al. 2002; Lange & Graham 1993; Lay 1979; Pickup 1998). These factors are likely to offset any growth benefits of increased atmospheric CO_2 concentrations, particularly given the poor nutrient status of soils across the property (Facelli & Temby 2002; Pickup 1991).

There is little published research about the potential impact of climate change on the specific World Heritage values of Willandra Lakes Region. The extensive literature on the property deals mainly with its archaeological and geological features, such as cremation practices and shell middens (Johnston & Clark 1998). Published literature contains discussion of past climate change but does not offer detailed projections on how variations in temperature, changes to rainfall patterns, or the frequency of storms and fires might affect the heritage values of the property.

Addition of the Willandra Lakes Region to the World Heritage List reflects two criteria, with specific values conferred by the property's significance both as '*an outstanding example representing major stages in the planet's evolutionary history and significant ongoing geological processes*' and for its '*testimony to past civilization*'. These values are essentially concerned with geomorphic attributes, which are not expected to be significantly affected by climate change (Goudie 2003; Sharples 2002; Swart 1994).

8.3.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criterion

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Values include:

Non-glaciated, low-latitude lacustrine landscape lake basins; fossil dunes and lake sediments with evidence of giant extinct marsupial species, evidence of past salinity fluctuations and landscape stability, and evidence of the area's response to major climate change.

The Willandra Lakes Region is not threatened by inundation from sea level rise or sustained increases in streamflow. Climate change is unlikely to result in a return to past environments characterised by long-lived flooding of the lakes and their interconnecting watercourses. Although overall trends appear to point to a drier, hotter and possibly windier region (CSIRO 2006), episodic localised events will occur as they have over the past 15,000 years.

Although erosion is a natural process, accelerated erosion may be detrimental to Pleistocene burials. For example, the human fossil trackway site is the largest in the world and dates to the Pleistocene epoch. The site was buried to protect it from sand blasting in 2007. Ground-penetrating radar shows that roughly 80% of the track is still concealed beneath a blanketing dune that is susceptible to wind erosion. Any increase in the intensity of this destabilisation will place additional pressure on attempts to monitor the exposure of the archaeological and palaeontological record.

The most likely impact of climate change on the geomorphology of the property appears to be localised accelerated erosion, in particular that attributable to storms, and a broader pressure on vegetation that stabilises dunes and watercourses. This vegetation includes a number of grasses, including white top (*Danthonia caespitosa*) and windmill grass (*Chloris truncata*), along with tree and shrub species such as sugarwood (*Myoporum platycarpum*), saltbush (*Atriplex stipulata*) and bluebush (*Maireana sedifolia*), which are discussed below. That pressure is expressed as lower recovery rates after fire or other natural events, and after grazing. A range of studies have indicated vulnerability to erosion after grazing (Foran 1984; Graetz & Wilson 1984; Landsberg et al. 2002; Lange & Graham 1993; Lay 1979). That might be particularly the case if pest numbers increase through migration from other locations, and through attenuation of controls such as the rabbit calicivirus disease. NSW National Parks and Wildlife Service notes that goats and other animals are attracted to tanks and other water on parts of the property, which occasionally results in scalds.

Specific impacts on the World Heritage values are uncertain, with disagreement about the nature of contributing factors and their intensity (Facelli & Temby 2002; Lay 1979; Pickup 1991, 1998; Vesk & Westoby 2001; Wilson et al. 1987). This is an area for further research, in relation to the Willandra Lakes Region and other sites.

Stunted bluebush and saltbush on the lake floor showing evidence of final saline phases of lakes.

The Willandra Lakes Region contains a range of flora, including *Eucalyptus largiflorens*, *Muehlenbeckia cunninghamii*, *Eragrostis australasica*, *Sclerolaena tricuspis* and *Alectryon olefolius* subspecies *canescens*. However, the property's World Heritage values stem from the chenopods pearl bluebush (*Maireana sedifolia*), stunted blue bush (*M. pyramidata*) and bladder saltbush (*Atriplex stipulata*) (Foran 1984; Graetz & Wilson 1984; Maconochie & Lay 1996). Increased CO_2 levels may benefit some plant species (Johnson et al. 1993), but there are grounds for caution in projecting substantial positive impacts through climate change. The poor nutrient status of these soils and competition among species are likely to negate the growth benefits derived from an increase in atmospheric CO_2 concentration (Facelli et al. 2005; Facelli & Temby 2002). Reduced water availability would also reduce ability to utilise increased CO_2. Pearl bluebush (*M. sedifolia*) abundance may decrease with climate change as black bluebush (*M. pyramidata*) increases, while weed species such as Ward's weed may increase with the loss of inter-bush grasses *Austrostipa* spp. Changes such as this would be expected to impact adversely on vertebrate and invertebrate species diversity.

Nevertheless, the relationship between potential climate change (e.g. longer droughts and higher temperatures), chenopod morbidity and vulnerability to threats such as fire and grazing, at the property level—as distinct from research on the species generally and on other arid landscapes (Capon 2002; Cofinas & Creighton 2001; Friedel 1984)—is unclear. Studies over the past 20 years advise caution in making inferences about overall growth of vegetation and the performance of particular species in arid rangelands (Vesk & Westoby 2001; Watson et al. 1997; Wilson et al. 1987). Potential long-term impacts of climate change on avifauna, reptiles and mammals associated with the chenopods are less certain.

Impact on cultural values

Cultural criterion

Criterion (iii): To bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared.

Values include:

Landforms and locations that greatly extend our understanding of Australia's environmental and Aboriginal cultural history, including exposures of sedimentary sequences that reveal Pleistocene sedimentary profiles and associated archaeological and palaeontological materials.

The Willandra Lakes Region is a geographically extensive and rich repository of artefacts and remains, reflecting a human presence for at least 50,000 years. The publications cited in the *Australian National Periodic Report* (2002) for the property and other works noted in the bibliography for this document testify to the importance of Willandra Lakes Region for archaeology. The excavations in Mungo National Park are especially important (Ashley et al. 2003). It is also important to note that archaeological material is not restricted to a particular location, but is found in locations across the property (Johnston & Clark 1998). Not all locations have been discovered. That is unsurprising, given the size of the property, its remoteness, the nature of the material, challenges to access and the resources available for comprehensive excavation. Some locations remain to be fully assessed and a cautious approach has been adopted in dealing with surface material in areas of particular vulnerability.

Eroding aeolian sediments, Lake Mungo lunette. *Geoff Larmour and the Department of the Environment, Water, Heritage and the Arts*

8.3.4 Associated threats

Threats to the archaeological values of Willandra Lakes Region (and concerns for Indigenous people who have an association with the area) are somewhat different from those in northern Australia and the Greater Blue Mountains properties. Although visitation numbers show an upward trend, doubling since the 1980s, the property is remote and is not experiencing the intense tourist traffic evident at Uluṟu-Kata Tjuṯa. The dispersion and nature of material means that the property is arguably less vulnerable to vandalism and predation than some other properties. Overall, visitation by non-specialists appears to be restricted to a fairly small zone. It is unlikely that visitation will increase significantly as a result of climate change. Higher temperatures and more frequent droughts of longer duration may deter casual visitors from experiencing a locale that one scholar characterised as 'like visiting Mars on a hot windy day' (Levin 2006, pers. comm.).

The greatest risk to archaeological and cultural material is through the natural processes of erosion, which may be accelerated by the impact of grazing animals such as sheep, kangaroos, rabbits and goats. With 70% of Willandra Lakes contained within pastoral lease land, grazing and soil management practices—particularly through periods of extended drought—are critical to soil stability. The decisions and actions that landholders take in the face of climate change are potentially significant to the conservation of World Heritage values for which the area is listed.

Climate change is unlikely to pose new and significant threats to specific World Heritage values. Isolated events, such as localised inundations, are likely to inconvenience researchers, either directly on an excavation site, or by inhibiting access. Overall, the material is generally stable, particularly when remaining in situ rather than excavated or exposed through natural processes such as dune movement and scalds. The potential for deterioration of artefacts and remains, through changes in the watertable and increased salinity, is unclear.

One possible vulnerability is from wildfire, although reductions in vegetation cover, if temperatures and water stress increase, may reduce the likelihood of large-scale fires. Reductions in the abundance and extent of vegetation, particularly in critical dunes and watercourses may, however, increase risks stemming from erosion and deposition.

8.3.5 Gaps in knowledge and future directions

In the context of climate change, the following issues need to be addressed for the Willandra Lakes Region and its values:

- To assess likely impacts of climate change, more needs to be known about the ecosystems of the property, including the identification of fauna, species interrelationships and the vulnerabilities of threatened species to climate change. An inventory and monitoring of species and their vulnerabilities would be desirable, particularly in relation to climate change interaction with other threats including changing fire regimes, and increased pressure by feral animals such as rabbits and foxes.
- Although there is extensive research on how climate change has affected the geomorphology of the region and human habitation in the past, there is an absence of authoritative research analysing how climate change might affect Willandra Lakes Region's World Heritage values in future.
- As with other World Heritage properties, there is a need to identify and communicate information about the potential impacts of climate change on the Willandra Lakes Region as a World Heritage area to a range of stakeholders, including Indigenous people. The site is not divorced from contemporary culture. Improved communication should be included in improving management strategies.
- Climate change may affect particular archaeological sites, in particular through erosion and deposition. While the extent of the likely impact of climate change is unclear, it is apparent that the loss of archaeological material once exposed by erosive processes is rapid. A systematic survey of the region, including special emphasis on the identification of fragile sites (e.g. surface sites) would be of value.

8.4 Lord Howe Island Group

View of Mt Lidgbird from Mt Gower. *Melinda Brouwer and the Department of the Environment, Water, Heritage and the Arts*

8.4.1 Climate change scenarios for Lord Howe Island Group

Climate change scenarios for New South Wales (noting that Lord Howe Island is well offshore and so this regional scenario may not be entirely applicable), relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[18]

- Average annual air temperature is expected to rise by 1.3 °C ± 0.6 °C by 2030.
- Average annual rainfall is unlikely to change, but seasonality of the rainfall may vary, with less rainfall in winter and spring and more in summer and autumn. Higher evaporative demand will mean that conditions are likely to become drier which, together with rising sea surface temperatures, is likely to affect plant and seabird life.
- Sea surface temperatures are expected to warm by 1–2 °C and seawater pH to decline by 0.2 units by 2070 (Hobday et al. 2006). Annual and seasonal ocean surface and island air temperature increases of 0.6–1.0 °C have been recorded since 1910 throughout a large part of the region south-west of the South Pacific Convergence Zone (IPCC 2007).
- Sea level is expected to rise by about 17 cm by 2030.[19]

18 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

19 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

8.4.2 Summary of impacts

The Lord Howe Island Group (31°30'–31°50'S, 159°00'–159°17'E) includes a series of oceanic islands and rocks comprising Lord Howe Island and the Admiralty Group (immediately to the north-east of Lord Howe Island); Mutton Bird and Sail Rock (just east of the central part of Lord Howe Island); Blackburn (Rabbit) Island (in the lagoon on the western side of Lord Howe Island); Gower Island (just off the southern tip of Lord Howe Island); and Ball's Pyramid (25 km south-east of Lord Howe Island), together with a number of other smaller islands and rocks. It is situated 717 km north-east of Sydney and 570 km from the Australian coast. It was inscribed on the World Heritage List in 1982. The Lord Howe Island Board is responsible for the conservation and management of the island's natural heritage values.

The island is an eroded volcanic remnant and has a number of outstanding geological features, including the cloud-covered summits of Mt Gower and Mt Lidgbird, as well as an extensive lagoon reef system. The reef is the world's southernmost true coral reef system. About 74% of the shoreline is exposed to the open ocean and is particularly vulnerable to the impacts of wave action generated by storm events, as well as to the impacts of sea level rise, and changes to the ocean temperature and chemistry.

The consequential impacts of a rise of the cloud layer, caused by rising sea surface temperatures, constitute a major climate-related threat to the island's plant communities. This cloud layer provides a source of precipitation (occult precipitation [20]) and maintains the humidity required by about 86% of the island's endemic plant species including the dwarf mossy forest that dominates the summit of the peaks on Lord Howe Island.

Seabirds may also be at risk from changes in the abundance and distribution of marine food caused by climate change in combination with other threats, such as intensive fishing activities.

8.4.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criteria

Criterion (vii) To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Criterion (x) To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Values include:

Diversity of spectacular and scenic landscapes within a small area and outstanding underwater vistas.

The Lord Howe Island Group is renowned for its exceptional diversity of spectacular scenic landscapes and underwater vistas containing the world's southernmost true coral reefs. Wind and wave action are major threats to the natural landscape. Several studies have focused on wave and climate impacts on the coastline of the island (Dickson & Woodroffe 2002; Dickson et al. 2004). The coastal morphology is locally sensitive to the effects of global climate change while some rock types, such as the consolidated calcarenite [21] rock forms, are more sensitive to wave action. There is also potential for crumbling coastal cliffs and rocky shore platforms to undergo extensive erosion as a result of sea level rise and severe storm events.

20 Precipitation derived from mist, fog, dew or cloud.

21 Rock that was deposited primarily as sand dunes.

Mt Lidgbird with cloud. *Melinda Brouwer and the Department of the Environment, Water, Heritage and the Arts*

It is difficult to accurately predict future climate change impacts on the coastal geomorphology of the island. If global climate change causes adjustments to sea level impacts on the cliffs, it will influence the rate at which erosion occurs and the nature of the erosional landforms themselves. It is difficult to extrapolate the island's geomorphological history to forecast the patterns of erosion that might be anticipated under conditions of global climate change (Dickson & Woodroffe 2002).

Diversity of vegetation communities.

Lord Howe Island is renowned for its diversity of indigenous vascular plants, which includes 241 species—some of conservation significance and many of which are endemic. There are 16 endemic plant species considered endangered, rare and vulnerable, with restricted ranges (Pickard 1983a, 1983b, 1984). However, some of the island's plant genera are also commonly found throughout the Pacific and on the Australian mainland. These include *Alyxia*, *Dracophyllum*, *Elaeodendron*, *Elaeocarpus*, *Metrosideros*, *Ochrosia*, *Psychotria* and *Sophora* (Auld & Hutton 2004). Many of these non-endemic plant genera are food sources for the island's fauna (Auld & Hutton 2004; Cassis et al. 2003) and provide an essential habitat for seabirds (Harris et al. 2005). There is a direct correlation between vegetation thickness and the number of bird burrows (Harris et al. 2005). However, burrowing seabirds also create ideal habitats for exotic plant species (Pickard 1984).

Change in the semi-permanent cloud cover that envelops the summits of Mt Gower (875 m) and Mt Lidgbird (777 m) is a major climate-related threat to the vegetation communities of the island (Garnaut 2008). The precipitation provided by this cloud cover and the humidity it provides during periods of low rainfall are important to summit vegetation communities. The precipitation derived from the cloud layer is also an essential source of water for flora and fauna at lower elevations. Similarly, about 31% of the gross annual precipitation in the Wet Tropics of Queensland is derived from occult precipitation, representing a significant contribution to the entire hydrological flow, particularly during periods of low rainfall (McJannet et al. 2007). The 'lift-cloud-base hypothesis' states that the climate of tropical mountains is showing signs of gradual change due to an elevation in sea surface temperatures (Pounds et al. 1997, 1999; Still et al. 1999). The disappearance of about 20 frog species in the highland forests of Monteverde, Costa Rica, was closely linked to changes in the extent of mountain mist following an increase in warmer temperatures (Pounds et al. 1999). Further rises in sea surface temperatures may lead to an elevation of the cloud layer on Lord Howe Island. The likely impact on the cloud forests and the fauna that they support is largely unknown.

View of Mt Lidgbird from Mt Gower with palm tree. *Melinda Brouwer and the Department of the Environment, Water, Heritage and the Arts*

Of the 42 endemic plant species, 36 (86%) are confined to the higher slopes and mossy cloud forest regions on Mt Gower (Harris et al. 2005; Pickard 1983a, 1983b). These endemics include *Blechnum contiguum*, *Corokia carpodetoides*, *Cyathea brevipinna*, *Hymenophyllum moorei* and *Leptopteris moorei* (Harris et al. 2005). There are also four species of fern (*Sticherus lobatus*, *Marattia howeana*, *Blechnum geniculatum* and *Polystichum whiteleggei*) with highly restricted ranges (Harris et al. 2005). A rise in the mossy cloud layer may lead to the decline or disappearance of most endemic plant species. Those plant species located over 750 m above sea level (ASL) are at greatest risk and include *Lepidorrhachis mooreana*, *Blechnum fullagarii* and *Olearia mooneyi* (Harris et al. 2005). There are also several plant species not confined to the upper slopes and summit of Mt Gower, such as *Cyathea howeana*, *Grammitis diminuta*, *G. nudicarpa*, *G. wattsii*, *Lepidorrhachis mooreana* and *Leptospermum polygalifolium* (Harris et al. 2005). The impact of a lift in the cloud layer on these plant species is unknown. Finally, the effects of climate change may limit the capacity of many indigenous species to shift in response to a change in temperature or sea level rise.

Diversity of bird taxa and unique bird breeding habitats.

The Lord Howe Island Group provides unique and important seabird breeding habitat. There is mounting evidence that climate change is having a substantial impact on seabird populations around the world (Barbraud & Weimerskirch 2001, 2006); however, in comparison to the northern hemisphere, there are few studies that examine the impacts of climate change on southern hemisphere seabird populations (Chambers et al. 2005). The population numbers of the migratory flesh-footed shearwater (*Puffinus carneipes*) on the island have declined substantially over the last few decades (Priddel et al. 2006). Long-line fishing is viewed as a major threat to these seabirds. Although Japanese long-line fishers ceased operations in 1997, the expanding domestic fisheries industry has continued to operate off the east coast of Australia (Baker & Wise 2005), resulting in the estimated death of 4,500 flesh-footed shearwaters annually between 1998 and 2002. Many of these birds probably originated from populations based on Lord Howe Island (Baker & Wise 2005).

The decline in seabird populations may also be associated with changes in food supply caused by changes in the marine environment. However, more research and long-term monitoring is required to determine if this observation is due to climate change or to other factors such as fishing activities (Baker & Wise 2005). Many of the seabirds on Lord Howe are likely to be affected by climate change through changes in sea surface temperatures and the associated changes in the abundance or distribution of prey. However, few studies have been conducted, and there is no long-term monitoring of these species. Long-term studies of some key indicator species are needed (D Priddel 2006, pers. comm.).

Changes in ocean temperatures and marine productivity may be a contributing factor to the decline of seabird populations. North American studies show a 90% decline in the numbers of sooty shearwaters (*Puffinus griseus*) associated with an increase in sea temperature (Veit et al. 1996). Changes on land may also be contributing to a decline in seabird populations. The health and composition of Lord Howe Island's vegetation has had a large impact on the number and distribution of bird burrows (Harris et al. 2005).

Unique terrestrial invertebrates.

The island is an important refuge for many terrestrial invertebrate species that have either become extinct, or fallen in numbers, on the Australian mainland (Auld & Hutton 2004). Insects typically respond to climate change by migrating to more climatically favourable regions, rather than face the prospect of extinction or of having to adapt in situ (Hill et al. 2002). Many species may be vulnerable due to their limited ability to easily migrate to the mainland. The stick-insect (*Dryococelus australis*) was thought to be extinct until it was rediscovered in a small population on Ball's Pyramid (Priddel et al. 2003). The habitat of this species is regarded as extremely fragile and unstable, and a management strategy has been proposed to ensure its long-term survival (Priddel et al. 2003). This recent find demonstrates the capacity for small invertebrate populations to avoid extinction in an unstable environment and that facultative parthenogenesis [22], which is common among insects and reptiles, allows low population levels to

22 Offspring are normally produced sexually but can also reproduce asexually in the absence of males—also called a 'virgin birth'.

recover from catastrophic events (Priddel et al. 2003). The Australian Museum completed an altitudinal invertebrate study on Mt Gower in 2006. The results of this study will provide useful long-term baseline data to monitor future changes.

The accidental introduction of black rats (*Rattus rattus*) in 1918 caused the extinction of two large land snails and five bird species on Lord Howe Island. Rats are a significant ongoing problem, and have an impact on native species through competition and predation. The surviving endangered land snail (*Placostylus bivaricosus bivaricosus*) remains at risk from rat predation, as does the large land snail (*Gudeoconcha sophiae*). The black rat is also implicated in the extinction of the Lord Howe Island phasmid (*Drycocelus australis*) from the main island. While the impact of climate change on rats is not known, it is likely that the generalist traits that favour invasive species versus more specialised species will also favour them in the face of climate change, in that they can more readily take advantage of disturbance across the landscape.

Coral reef systems.

An extensive chronostratigraphic study of the island has revealed that the coral reef system was considerably more extensive during the mid-Holocene period (Woodroffe et al. 2005, 2006), indicating that sea surface temperatures were warmer in that period. However, the decline in the extent of coral reefs around Lord Howe Island since the mid-Holocene is likely to result from progressive changes in lagoon morphology (e.g. infilling) rather than from a change in sea surface temperature (Woodroffe et al. 2005). This, and similar studies, clearly suggest that factors other than climate influenced the past distribution and abundance of coral on the island. Time periods when reefs were more extensive, at marginal locations such as Lord Howe Island, need to be examined to see whether they provide evidence of warmer conditions, or whether there are other explanations for past expansion and contraction (Woodroffe et al. 2005).

The growth and recruitment of temperate corals is greatly influenced by water temperature, seasonal factors, nutrient loads and competition with macroalgae (Harriot 1992; Harriott et al. 1993, 1995). Overall, the coral reef systems of the island appear to be in reasonably good condition (S Swearer 2006, pers. comm.). Some coral bleaching and a population increase in the crown-of-thorns starfish were reported during the late 1990s, but these threats have had little impact on the quality of the reef community (Environment Australia 2002). The corals around the island are dominated by species that reproduce by releasing brooded planulae, as opposed to those species that reproduce by mass release of spawned gametes, which is common among the Great Barrier Reef corals (Harriott 1992; Harriott et al. 1993).

Coral species adapted to warmer conditions may have an adaptive advantage over the cool-water species in the face of rising sea surface temperature, but further confirmation is required. This would also have important implications for the conservation of warm-water coral species. In addition, there is some debate about whether the recruitment of coral is dependent on replenishment of coral larvae from reefs at lower latitudes, such as the Great Barrier Reef (Harriot 1992). However, if Lord Howe Island loses most of its corals due to regional or global climate change, they are unlikely to be replaced by a significant influx of warm-adapted coral genotypes from the north (Ayre & Hughes 2004). Furthermore, the probability of coral larvae travelling from the northern latitudes and being intercepted by a small island such as Lord Howe Island is extremely low (Harriott 1992).

Apart from coral bleaching, an increase in ocean acidification is a major concern for the conservation of the world's coral reefs. Acidification is caused by carbon dioxide dissolving in water to produce carbonic acid, increasing the acidity of the oceans (Feely et al. 2004).

The resulting acidification could prevent calcifying organisms—such as corals, shellfish and some species of phytoplankton—from producing calcium carbonate and prevent shell formation. Coral communities around Lord Howe Island are likely to be affected if the oceans become more acidic.-

There are no experimental studies examining the sensitivity of cold-water coral reef systems, such as those at Lord Howe Island, to CO_2-induced ocean acidification. However, it is expected that acidification will affect the recruitment of cold-water corals more than their warm-water counterparts, because the carbonate saturation state is generally lower at higher latitudes than at lower latitudes (The Royal Society 2005). Studies suggest that cold-water coral reef systems are likely to face extinction if aragonite [23] saturations levels continue to decline. The ocean-wide decrease in aragonite saturation level is likely to decrease cold-water coral calcification. Large areas of the oceans may also become completely uninhabitable for cold-water corals (The Royal Society 2005).

Tropical and temperate taxa of marine flora and fauna.

Numerous studies suggest marine ecosystems, including intertidal communities, are responding to changes in sea surface temperatures. However, it is difficult to ascertain if the observed changes in recruitment and density of fish stocks are due to climate change or to other factors, such as fishing activities. In the North Atlantic, variations in sea surface temperatures and sea surface wind patterns have been linked to changes in fish recruitment (Stenseth et al. 2002). These marine population changes may be linked to climatic oscillations such as the Pacific Decadal Oscillation. In the Pacific, researchers have associated changes in fish stocks with increased ENSO activity (Bunce et al. 2002). These climatic oscillations are responsible for changes in primary production of biomass from strong upwelling of deep nutrient-rich waters (Francis & Hare 1994).

Lord Howe Island provides a unique opportunity to study fish migratory patterns in response to climate and changes in seawater temperatures. The relationship between fish migration along the Eastern Australian Current and changes in sea surface temperature requires further investigation. Any change in fish migration and recruitment is also likely to affect seabird populations on Lord Howe Island.

The shallow water and marine shelf environments of the island contain several endemic fish species including McCulloch's anemone fish (*Amphiprion mccullochi*), frill goby (*Bathygobius aeolosoma*), longfinned leatherjacket (*Cantherhines longipinnis*) and Lord Howe Island pipefish (*Syngnathus howensis*). Many of the endemic species in the island's marine environment are abundant, with no observable change in population over the last five years. However, it is difficult to predict what impact rising sea surface temperatures might have on the distribution and abundance of fish species.

The impact of ocean acidification on coral reefs may also have ramifications for associated marine organisms and ecosystems, such as sea grasses (The Royal Society 2005). In addition, some benthic organisms and echinoderms are highly sensitive to changes in acidity (Shirayama et al. 2004).

Marine invertebrate species.

Ten per cent of the 143 marine invertebrate species of the island system are endemic (Ponder et al. 2000, 2001). Many species have not been recorded or are under-represented in surveys. There are 83 species of corals and 65 species of echinoderms, of which 70% are tropical. Corals have been studied in far more detail than other marine invertebrates, and much more is known about their physiology and sensitivity to climate change. Very little is known about the biology of smaller-sized marine invertebrate taxa, or about those species inhabiting deeper waters (Ponder et al. 2001).

Marine invertebrates having an 'intrinsic' or direct form of reproduction, in which there is no long-distance dispersal mechanism such as mobile larvae, are probably more susceptible to the effects of climate change because of their inability to relocate. Fourteen per cent of echinoderm and mollusc species with limited dispersion abilities, which were surveyed in temperate marine waters around Victoria, were restricted to cool temperature regions and could face localised extinction if water temperature rose by 1–2 °C (O'Hara 2002). In addition, the incidence of disease in marine invertebrate organisms is greatly enhanced in reef systems that have become severely degraded (Harvell et al. 2002).

23 Aragonite is a carbonate mineral, one of two common naturally occurring forms of calcium carbonate.

Mt Lidgbird. *Melinda Brouwer and the Department of the Environment, Water, Heritage and the Arts*

8.4.4 Associated threats

Rats are one of the biggest threats to the wildlife of Lord Howe Island as mentioned above. Further to the threats they pose to the land invertebrates, two species of lizards—the Lord Howe Island gecko (*Christinus guentheri*) and Lord Howe Island skink (*Pseudemoia lichenigera*)—are scarce on the main island of Lord Howe where *Rattus rattus* occurs, but occur more abundantly on other small islands in the Lord Howe Island Group where the rat is absent.

Invasive weeds and fungi (e.g. *Phytophthora cinnamomi*) may pose an increased risk to the island's natural values as the climate warms. Fleshy-fruited weed species, such as *Psidium cattleianum* and *Cotoneaster glaucophyllus*, have the capacity to affect forest structure and dynamics. These weeds are considered a major threat to endangered species such as *Carmichaelia exsul* and *Calystegia affinis* (Auld & Hutton 2004). A weed and pest inventory, to assess the extent of the problem, was undertaken in 2006 (T Auld, pers. comm.). A weed control strategy has been implemented to address this ongoing problem.

The potential for new marine pest invasions from regular shipping activities poses an ongoing major threat to the marine World Heritage values of the island. While the potential for changes resulting from global warming to alter the rate of incursions from ballast water or from marine 'hitchhikers' on the outsides of vessels is not known, increasing sea surface temperatures in the marine corridors used by the vessels may allow survival of inshore species that previously were killed by transition through cold waters.

The impact of climate change on existing introduced species occurring in the Lord Howe Island Group, not yet causing problems but known to act invasively elsewhere (e.g. the crown-of-thorns starfish), is not known but of major concern to park authorities, even though the impacts from this invasive organism have so far been minimal (S Swearer 2006, pers. comm.).

8.4.5 Gaps in knowledge and future directions

There are a number of issues to be addressed in respect of future climate change and Lord Howe Island. For example:

- Potential biological and hydrological impacts resulting from a change in the mossy cloud layer require further investigation. There are some opportunities for collaborative research in the Wet Tropics of Queensland. Research into the propagation and ex situ storage techniques of species restricted to the cloud forests is required (Harris et al. 2005). This may include both seed banking and/or forming living collections. The NSW Department of Environment and Climate Change is collecting and learning more about propagating species from the mist forest, with a view to establishing a collection of plants in the island's nursery.
- The marine environment of the Lord Howe Island Group is changing in response to rising sea surface temperatures. Changes in marine population dynamics are impacting on the ability of bird species, such as the flesh-footed shearwater (*Puffinus carneipes*), to successfully forage for food. Very little is known about the possible impacts of climate change on bird populations in the southern hemisphere. Long-term monitoring of bird populations is required.
- A better understanding of the extent of genetic diversity among endemic fish species might provide some insight into the capacity of some species to adapt to environmental change. Studies examining the potential impact of rising sea temperature on marine fauna populations need to be continued.
- High-resolution mapping would assist in the development of a climate change risk assessment and management program for marine life around Lord Howe Island (S Swearer 2006, pers. comm.).
- Very little is known about the biology of the smaller-sized marine invertebrate taxa or of deep-water species. Research into the recruitment and reproduction of temperate coral species is required.
- Marine pest invasions from regular shipping activities are a major threat to the island's marine World Heritage values. A comprehensive survey and assessment of marine pests—including the potential for new marine pest invasions from regular shipping activities and for emergence of 'sleeper' species such as the crown-of-thorns starfish—is needed to inform development of a future climate change management plan.
- While there is no climate change action plan for Lord Howe Island, the Lord Howe Island *Biodiversity management plan* (NSW Department of Environment and Climate Change 2007) contains six recommendations relating specifically to climate change impacts, including:
  - establishing biodiversity monitoring sites in as many at-risk locations as possible
  - establishing long-term monitoring sites of fauna and flora along an altitudinal gradient in the southern mountains
  - undertaking research to monitor the impact of climate change on seabird populations
  - developing and implementing a monitoring program to assess the impact of climate change on invertebrate lifecycles and at-risk flora
  - establishing a climate monitoring station on Mt Gower.

8.5 Tasmanian Wilderness

Ballroom Forest at Cradle Mountain. *Nicola Bryden and the Department of the Environment, Water, Heritage and the Arts*

8.5.1 Climate change scenarios for Tasmania

The following climate change scenarios for Tasmania, relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[24]

- The average annual temperature for this World Heritage property is expected to increase by 1.1 °C ± 0.4 °C by 2030.
- Annual average rainfall is likely to increase by 3.5% ± 11% by 2030, although this is likely to be seasonally variable, with summer rainfall likely to fall by around 7.5% (±15%).
- Sea level is expected to rise by as much as 17 cm.[25]
- The severity and frequency of drought is expected to increase, and the number of days of high fire frequency may increase slightly (0.5 day per year).
- There is likely to be a 10–40% reduction in snow cover by 2030 (Hennessy et al. 2003).
- Although evaporation rates will increase (4.4% ± 1.9%), streamflow response is likely to be unpredictable (±10% change) (Chiew & McMahon 2002).

24 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

25 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

8.5.2 *Summary of impacts*

The Tasmanian Wilderness World Heritage area covers an area of 1.38 million ha or 20% of Tasmania. The coastal regions of the Tasmanian Wilderness are considered likely to experience the most dramatic climate change impacts, associated with sea level rise. Coastal regions contain important geomorphic and pedological [26] values, most of which are non-renewable even if climate change drivers are reduced or reversed. As well as their intrinsic geomorphic values, sandy coasts also support significant biotic communities and Aboriginal cultural values. Many Aboriginal sites, such as middens, sea cave deposits, rock art and cave art sites, rely on preservation of underlying landforms. While the potential exists for some biotic communities to 'migrate' landwards, management of non-renewable cultural and geomorphic features and systems will require significant consideration.

Anthropogenic climate change is also likely to affect rates and magnitudes of change in other landscape provinces, including fluvial systems, karst and in the extensive blanket bogs supporting buttongrass ecosystems that characterise much of south-western Tasmania. It will be important to investigate and monitor landscape-scale linkages between biotic and geomorphic systems, particularly in the buttongrass moorlands where fire plays a key role in controlling hydrological responses to changes in rainfall, evapotranspiration and temperature. This in turn controls shallow groundwater and streamflows, which influence vegetation distributions—habitat for buttongrass moorland biota, such as the endangered orange-bellied parrot.

In montane and subalpine areas, a change in fire regimes may affect fire-sensitive conifer species—including huon pine, pencil pine and King Billy pine—and is likely to cause a significant decline in the populations of fire-sensitive conifer species including alpine species such as *Pherosphaera hookeriana*, *Diselma archeri* and deciduous beech (Tasmanian Department of Primary Industries and Water, pers. comm.). Changed fire regimes have also resulted in landscape changes from extensive erosion.

This section of the report provides a general assessment of the vulnerability of the Tasmanian Wilderness to climate change impacts, identifies World Heritage values within the property that are highly vulnerable to climate change impacts and identifies major gaps in knowledge of the vulnerability of the World Heritage values to climate change impacts.

8.5.3 *Potential climate change impacts on World Heritage values*

Impact on natural values

Natural criteria

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Criterion (x): To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Values include:

Geological, geomorphological and pedological features, systems and processes.

Geological, geomorphological and pedological features, and systems of the Tasmanian Wilderness, are described by Parks and Wildlife Service (2004) as in '*very good condition with natural rates and magnitudes of change in geomorphological and soil systems continuing unhindered*'. This forms a key value of the area, as described by Sharples (2003: 66).

26 Related to soil formation.

Cradle Mountain and Dove Lake. *Ross Scott*

However, on the Central Plateau in the north-east of the Tasmanian Wilderness, extensive erosion is regarded as a concern to the geoconservation values (Parks and Wildlife Service 2004). The Central Plateau has experienced severe sheet and streambed/bank erosion attributed to fire and past grazing activities with an estimated 10,000 ha affected by erosion (Cullen 1995). A rehabilitation strategy is currently being developed for these areas (Storey and Comfort 2007).

Changes in the periglacial terrain on the Central Plateau may provide a good indicator of the effects of temperature rise on pedological processes (Tasmanian Department of Primary Industries and Water, pers. comm.): '*Currently active periglacially-sorted ground on the Central Plateau may be a sensitive indicator of temperature rise. Although they are artificially maintained they appear to be at critical climatic limit—much more warming may significantly reduce their range or activity*'.

Key geomorphic and pedological systems likely to be vulnerable to anthropogenic climate change include the following key thematic areas:

- coastal landforms and processes
- karst landforms and processes (including glacio-karstic interactions)
- fluvial and lacustrine landforms and processes
- blanket bog organic soils and process systems
- glacial/periglacial landforms and processes.

Other more restricted classes of geomorphology and pedology within the Tasmanian Wilderness (such as lacustrine [27], aeolian [28] and mass movement systems) may also have climate change-related implications. While not of outstanding universal value in their own right, they support the integrated theme of ongoing natural processes, identified by Sharples (2003: 66).

Coastal landforms and processes.

The Tasmanian Wilderness contains the most extensive area of unmodified coastal environments in temperate Australia, '*the longest undisturbed stretch of high energy embayed temperate ("Roaring Forties") rocky and sandy coastline globally*' (Sharples 2003: 69). Their global significance lies in their undisturbed nature, and undisturbed conditions in the terrestrial catchments that deliver sediment to coastal systems. '*The undisturbed sandy coasts will prove especially valuable in a global context as benchmark sites that will allow monitoring of the geomorphic effects of sea level rise free of other complicating human disturbances*' (Sharples 2003: 69). Impacts to sandy coasts are likely to result from erosion due to sea level rise; redistribution of offshore sand masses; and potential alterations to wind and wave regimes that drive longshore drift, and processes of beach retreat, progradation [29] and sediment accumulation.

A Department of Primary Industries and Water project has commenced to accurately document the shoreline position on key sandy coasts within the Tasmanian Wilderness, as well as benchmarking associated vegetation communities. Based on accurate differential GPS and LIDAR [30] surveys, this work will continue to document effects of sea level rise and storm-surge events on coastal geomorphology and associated ecosystems.

Karst geomorphology and karst hydrology.

Karst systems are landscapes resulting from the dissolution of bedrock by natural waters. In the Tasmanian Wilderness, karst has developed in carbonate bedrock—limestone and dolomite. Extensive cave systems are common throughout the karst areas, including some of Australia's deepest and longest networks. Complex surface and underground hydrological systems are also characteristic of Tasmanian Wilderness karst areas.

The Tasmanian Wilderness is critical to karst management in Tasmania, containing about 63% of Tasmania's highly karstified rock. Over 80 individual karst areas are found in the Tasmanian Wilderness, ranging from alpine to plains karst, coastal karst and interstratal karst.[31] Hydrothermal karst systems such as that at Mt Weld are highly significant, as are palaeokarst caves and deposits of Permian to Devonian age (Sharples 2003). Exit Cave and the Weld catchment karsts are of global significance in their own right, and in their ability to contribute to other themes such as Ongoing Natural Processes and Late Cainozoic Ice Ages, where glaciokarstic interactions have proved highly significant (Houshold & Davey 1987).

More extreme rainfall events could lead to an increase in flash flooding and a further deterioration in water quality in sensitive karst areas, particularly within caves. However, it is unclear what impact climate change will have on karst hydrology in the future, given the degree of unpredictability in forecasting future streamflow for this property (Chiew & McMahon 2002).

27 Laid down in a lake environment.

28 A sandstone formed from wind-transported sediment.

29 Seaward buildup of a beach.

30 The LIDAR (Light Detection And Ranging) instrument is a method for collecting detailed terrain data over large areas.

31 Interstratal karst is where solutional landforms have developed below an impermeable caprock.

The combined effects of less predictable surface streamflow and increased evapotranspiration are likely to affect karst groundwater regimes to some extent. Karst groundwater is recharged through both surface streams sinking into cave systems, and through direct percolation of rainfall through soil and surface karst or epikarst.[32] While the effects of changes to surface streamflow are difficult to predict, it is likely that percolation flows will decrease. This is likely to affect the growth and chemical composition of speleothems [33], which are very sensitive recorders of environmental parameters such as average temperature and soil CO_2 characteristics. Speleothems are therefore an excellent potential source of information for monitoring changes in environmental parameters as climate change proceeds. As with coastal systems, these sources of environmental data form an extremely important baseline resource when found in areas remote from other human disturbance, such as the Tasmanian Wilderness. Watertable levels in karst may also be used as a 'window' to examine the effects of climate change on groundwater recharge (Tasmanian Department of Primary Industries and Water, pers. comm.).

The impact of fire on water quality is also an issue that could affect both surfacewater and groundwater quality. Additionally, wildfires have been shown to adversely affect surface solutional features by spalling. There is therefore a need to ensure that fires are properly managed in karst areas, in many cases through a policy of exclusion where necessary and possible (Tasmanian Department of Primary Industries and Water, pers. comm.).

Blanket bog organosols and process systems.

Blanket bog organosols [34] cover a large proportion of the Tasmanian Wilderness. They are of particular value in their own right, being the only example of a distinct type as compared to extensive northern hemisphere blanket bogs. This is due, in large measure, to the interaction of peat formation through decay of moorland vegetation and disturbance of sediments by the ubiquitous burrowing crayfish (genus *Engaeus*), whose burrows exert a significant control on shallow groundwater systems. This combination of substrate type and distribution, high organic content in soils, groundwater dynamics and bioturbation drives a blanket bog ecosystem (part of an entire landscape mosaic including scrub, wet sclerophyll and rainforest elements), which is internationally unique (Sharples 2003: 68). Environmental processes in the moorlands are also strongly linked to internationally significant aspects of fluvial landforms and processes (Sharples 2003: 68)—see below. Where alkaline (carbonate-rich) springs emerge from karst aquifers, distinctive, apparently barren 'scalds' (termed alkaline pans) have developed, supporting endemic floristic elements, including endemic genera *Winifredia* and *Ambuchamania*.

Many of the south-west buttongrass moorlands play a very important role in stabilising relict Quaternary landforms. Most important of these are the spectacular fluvial and marine terrace systems that flank Macquarie Harbour, and southwards beyond Port Davey. Terraces developed quickly (at least 100 m/million years) but their preservation has most likely been due to an extremely tough, intact blanket of organosols (incorporating densely woven root systems of *Restio*, *Gymnoschoenus* and *Melaleuca*, etc.). Higher fluvial terraces, over 500,000 years old, remain in almost perfect condition, preserving channel and bar features of prior streams. A flight of at least 15 well preserved marine terraces, ranging to 400 metres above sea level (best preserved at Birchs Inlet), may provide a detailed record of Quaternary sea level change and recent tectonic movements—an important context for management of anthropogenic sea level rise (Tasmanian Department of Primary Industries and Water, pers. comm.).

Moorlands also preserve significant subfossil deposits, some containing elements of rainforest flora, including coniferous species (e.g. Melaleuca Inlet). These are important in reconstructing vegetation history and rates of change in biogeographic distribution of flora and fauna. The palynological [35] potential of the area is little investigated; however, perennially inundated wetlands, free from the sediment disturbance of freshwater crayfish (e.g. Lake Selina), or particularly deep deposits (e.g. Darwin Crater), have yielded important records.

32 Epikarst is the upper surface of karst, consisting of a network of intersecting fissures and cavities that collect and transport surface water and nutrients.

33 Cave formations; secondary mineral deposited in a cave by the action of water.

34 Soils dominated by organic materials.

35 Reconstructing prehistoric environments from analysis of spores, pollen and certain algae usually from swamp sediments.

Buttongrass moorland vegetation is one of the most flammable communities in the world, burning at higher moisture contents than any other known plant community. They require just one or two rainfree days to be able to carry fire. This, in combination with the combustibility of the soil itself makes these systems particularly vulnerable to any increase in fire frequency, particularly of wildfires. Loss of organic carbon through increased wildfire frequency has the potential to degrade many of the values listed above, as well as supported flora and fauna. Oxidation and loss of the organic content of the soil is also a possibility if increased evaporation rates lead to increased drying of soil surface layers. This may lead to a significant loss to the atmosphere of CO_2, given the extent of organosols in the Tasmanian Wilderness.

Fluvial landforms and processes.

Sharples (2003: 67) outlined the significance of Tasmanian Wilderness fluvial systems in the following terms: '*Effectively undisturbed natural fluvial process systems of the Tasmanian Wilderness comprise the largest area of undisturbed temperate fluvial glacial-influenced systems free of contemporary glacial (glacio-fluvial) influences in the southern hemisphere and probably the world*', to which he assigns global significance. He nominates the *New–Salisbury River basin* and the *Birchs Inlet–Sorell River–Packer River tectonically influenced peatland fluvial system* as of outstanding significance; the New–Salisbury system because of its lack of European (and probably Aboriginal) influence on its development and current processes, and Birchs Inlet because of the unique effects of organosols and neotectonics on its streams (Sharples 2003).

The morphology of certain buttongrass river systems, such as the spectacularly meandering streams in the Birchs Inlet catchments, is globally very rare. These rivers have developed as a result of extremely tough boundary conditions on channel banks (resulting from a combination of dense root mats choking infertile organosols), in association with flashy hydrology [36] and abundant sediment supply. As a result, these streams show internationally extreme meandering forms. Geomorphic features and processes of other river types in buttongrass landscapes appear to be significantly controlled by the condition of bounding riparian scrub and forest—degradation by fire has apparently allowed significant widening and deepening of such channels.

While the effects of anthropogenic climate change on fluvial systems are generally speculative for the Tasmanian Wilderness, it is likely that any degradation of blanket bog organosols, either through oxidation or through direct combustion following increased wildfire, will have a flow-on effect in river systems. Any breakdown in the tough channel boundary conditions provided by organosols and associated vegetation will make channel banks highly susceptible to erosion, as they are often composed of unconsolidated quartzite sands and gravels with very low shear stress values.

Sea level rise associated with climate change may have a positive impact on the three meromictic lakes [37] associated with the Gordon River, possibly countering the rapid decline in meromyxis due to reduced penetration of salt water up the nearby river since construction of a dam in the middle reaches of the river. Maintenance of meromixis of the lakes relies on periodic saltwater incursions up the Gordon River (Hodgson et al. 1997).

Glacial/periglacial landforms and processes.

Glacial features in the Tasmanian Wilderness are of global significance as the best available record of temperate glacial processes during the late Cainozoic ice ages in the southern hemisphere, due to Tasmania's maritime climate, tectonic stability and diversity of glacial environments (Sharples 2003: 71).

These landform systems are essentially relict, the processes that formed them becoming inactive at the close of the Pleistocene epoch approximately 12,000 years before present. As such, they are non-renewable resources, so cannot be replaced should there be any acceleration in their loss through the effects of climate change. Many of the landforms (particularly erosional features) are robust; however, some depositional units may be at risk if erosional processes increase due to extreme rain events.

36 Hydrological patterns exhibiting unstable flow regime and increased stormwater runoff quantities.

37 Meromictic lakes comprise layers of water that do not mix.

Relict biota that show links to ancient Gondwanan biota including: endemic conifers, conifers of extreme longevity. Endemic members of large Australian plant families including relict species.

The main terrestrial plant communities of the Tasmanian Wilderness include the eucalypt forest, alpine vegetation, temperate rainforest, teatree scrub and buttongrass moorland. The buttongrass moorland community is dominated by buttongrass (*Gymnoschoenus sphaerocephalus*) and sedges, while the teatree scrub vegetation type is typically composed of *Banksia*, *Acacia*, *Melaleuca* and *Leptospermum* (Kirkpatrick 1991; Marsden-Smedley & Kirkpatrick 2000; Reid et al. 1999).

Tasmania has the largest population of primitive taxa and Gondwanan relicts of alpine flora in Australia, with a majority of the diversity located within the property (Balmer et al. 2004). The Tasmanian Wilderness has only nine plant species (alpine obligates) restricted to the alpine areas above the climatic treeline. These plant species include *Phyllachne colensoi*, *Dracophyllum minimum*, *Carpha rodwayi*, *Gaultheria depressa*, *Milligania lindoniana*, *Celmisia saxifrage*, *Cheesemania radicata* and *Oreomyrrhis sessiliflora* (Balmer 1991). Cool-adapted alpine species may have difficulty in adapting to a temperature increase due to their restricted range, whereas a warming trend may benefit temperate and rainforest plant species. Warmer seasonal temperatures and higher atmospheric CO_2 concentrations are also likely to change the composition of alpine vegetation with an expected increase in woody plant communities (Williams & Costin 1994). In buttongrass moorland regions, a change in vegetation density by heath and shrub species could lead to the formation of a 'closed canopy system' and result in the demise of some buttongrass species from increased shading (Marsden-Smedley & Kirkpatrick 2000). However, tendency for increased shading may be offset by increased burning frequency. Increased burning frequency would maintain the vegetation in a more open state than it is at present (current state reflecting that recent burning frequency has been low). Also, increased burning may result in depletion of nutrients and loss of peats, which would result in reduced growth rates. So the actual outcome is not clear; however, it seems unlikely that there will be many species at risk from canopy shading (Tasmanian Department of Primary Industries and Water, pers. comm.).

Climate change is likely to result in increased elevation of the climatic treeline. If there is a temperature rise of 1.5–1.9 °C, it is possible that the elevation of the treeline would move some 250–300 m above the present treeline. This would eliminate the true alpine zone in Tasmania and result in cool temperature-sensitive species potentially facing population extinction in Tasmania. This conclusion is based on assumptions that there will continue to be an adiabatic lapse rate [38] of 0.6 °C with each 100 m altitude rise, and that the increases would apply to the summer mean temperatures as well as to average annual temperatures. The impact that this temperature-associated vegetation change will have on fire regimes is not clear but it appears likely that the frequency of fire reaching mountain tops will increase, further degrading the condition of alpine communities (Tasmanian Department of Primary Industries and Water, pers. comm.).

There are about 80 endemic species and another 14 sub-specific endemic taxa that, although not specifically restricted to areas above the climatic treeline, are nonetheless fairly limited in their habitat preferences and are found largely in the alpine zone. Competition and changes in the dynamics of alpine communities may lead to serious declines in populations of many of these species. These include the threatened species *Colobanthus curtisiae* (listed as Rare at the state level and Vulnerable at the national level), *Planocarpa nitida*, *P. sulcata*, *Geum talbotianum* and *Pimelea milliganii* (all listed as Rare at the state level), which have alpine vegetation as their stronghold. Another species, *Sagina diemensis* (Critically Endangered at the national level), is a karst species that appears not to be tolerant of competition and may be impacted by any climatic changes that result in habitat changes in the two locations where it occurs (Tasmanian Department of Primary Industries and Water, pers. comm.).

In 2001–2002, altitudinal transects on Mt Weld were undertaken as part of a long-term climate change study. The site will be surveyed again in 2011–2012 to determine if climate change is having any impact on plant species. The Mt Weld transects were also established to monitor birds and invertebrates (Doran et al. 2003). Endemic conifers including the King Billy pine (*Athrotaxis selaginoides*) are extremely susceptible to dieback, and preliminary results of this long-term survey indicate that they are showing signs of retreat (J Balmer 2006, pers. comm.). Patches of dieback identified at Cradle Valley can probably be attributed to climate change (Balmer et al. 2004). Widespread dieback of eucalypts from drought and predation has also been reported (Kirkpatrick et al. 2000).

38 Adiabatic lapse rate is the rate at which temperature decreases with altitude.

Without doubt, fire is the greatest threat to the conservation of alpine vegetation (J Balmer 2006, pers. comm.). Rainforest and subalpine forests are sensitive to fire, and could be under threat from an increase in fire frequency and intensity. Pyrke and Marsden-Smedley (2005) produced a fire sensitivity index of TASVEG mapping classes in Tasmanian Wilderness. A change in fire regime (more intense and frequent) would have a much greater impact on conifers because they are often killed by fire and have extremely poor or limited dispersion range (Marsden-Smedley & Kirkpatrick 2000). Over the past 100 years, extensive pencil pine (*Athrotaxis cupressoides*) and King Billy pine (*Athrotaxis selaginoides*) populations have been destroyed as a result of wildfire (Balmer et al. 2004). Some tree species, such as the deciduous beech (*Nothofagus gunnii*), are also very sensitive to fire. These species are categorised as having extreme sensitivity to fire (Pyrke & Marsden-Smedley 2005). Because of their restricted distribution and sensitivity to fire, these coniferous montane forest species have been given conservation priority under the Tasmanian Regional Forests Agreement (1997) (Tasmanian RFA 1997). Table 6 summarises the vegetation communities that are likely to be the most vulnerable to fire under climate change.

Table 6. Vegetation communities likely to be most vulnerable to fire under climate change (Source: Pyrke & Marsden-Smedley 2005)

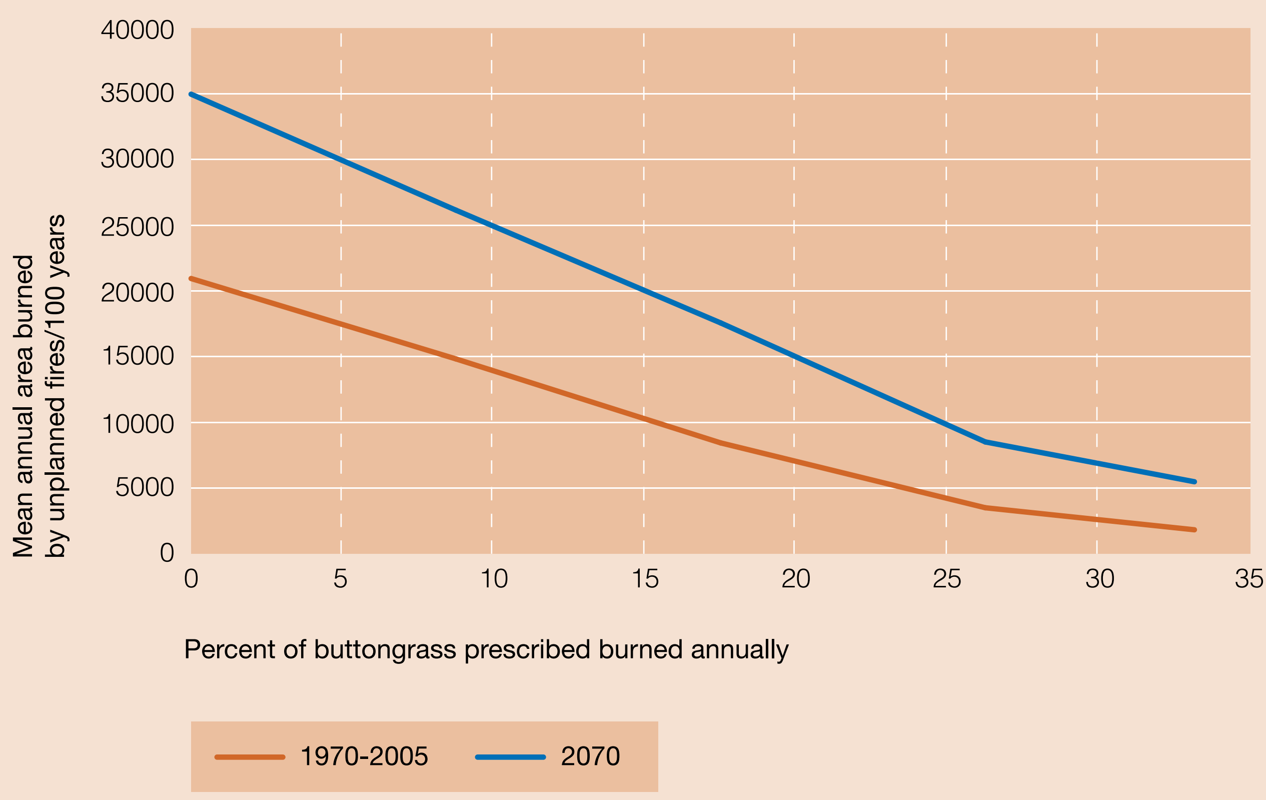
Vegetation community (type)	Fire sensitivity	Examples
Alpine and subalpine heathland with conifers and/or deciduous beech	Extreme	*Nothofagus gunnii* Pencil pine (*Athrotaxis cupressoides*) and King Billy pine (*Athrotaxis selaginoides*)
Alpine and subalpine heathland without conifers or deciduous beech	Very high	Subalpine *Diplarrena latifolia* rushland Subalpine *Leptospermum nitidum* woodland
Rainforest with conifers and/or deciduous beech	Extreme	*Athrotaxis selaginoides–Nothofagus gunnii* short rainforest *Lagarostrobos franklinii* rainforest and scrub
Rainforest without conifers or deciduous beech	Very high	*Leptospermum* with rainforest scrub *Nothofagus–Phyllocladus* short rainforest
Mixed forest (mixed rainforest and sclerophyll)	Very high	*Eucalyptus delegatensis* forest over rainforest *Eucalyptus nitida* forest over rainforest *Eucalyptus obliqua* forest over rainforest *Melaleuca ericifolia* swamp forest
Sphagnum	High	*Sphagnum* peatland
Wet sclerophyll forest	High	*Eucalyptus regnans* forest *Eucalyptus nitida* forest

Vegetation community (type)	Fire sensitivity	Examples
Alpine and subalpine sedgy and grassy	Moderate	Highland grassy sedgeland Highland *Poa* grassland Western alpine sedgeland/herbland
Dry sclerophyll forest	Extreme (E) to Low (L)	*Eucalyptus morrisbyi* forest and woodland (E) *Eucalyptus perriniana* forest and woodland (E) *Allocasuarina verticillata* forest (L) *Banksia serrata* woodland (L) *Eucalyptus amygdalina* (L)
Dry sclerophyll woodland	Low	*Eucalyptus viminalis* shrubby/heathy woodland *Eucalyptus ovata* heathy woodland
Buttongrass moorland	Low	Pure buttongrass moorland Restionaceae rushland Western lowland sedgeland

Buttongrass, heath and moorland extending over vast plains.

Buttongrass moorlands extensively comprise hummock-forming buttongrass (*Gymnoschoenus sphaerocephalus*). This vegetation type is highly fire-prone (Balmer et al. 2004) and, unlike other vegetation types (e.g. wet eucalypt forest, rainforest), the soil dryness index does not influence flammability (Marsden-Smedley et al. 1999). In other words, buttongrass moorlands are capable of burning even under wet conditions. Prescribed burning is often used as a management strategy to ensure that risk of wildfire spread to adjacent fire-sensitive forest communities (e.g. rainforest and alpine) is greatly reduced. Modelling work using FIRESCAPE has shown that by the year 2070 it will be necessary to almost double the amount of prescribed burning to realise the same level of area burnt by unplanned fires (Figure 4) (K King, pers. comm., unpublished data). This modelling showed that small shifts in rainfall and precipitation result in a large change to the area burnt. These results suggest that unplanned fires in buttongrass moorlands are likely to become more widespread by the year 2070, based on these very early CSIRO climate models (CSIRO 2001).

Figure 4. The effects of climate change on prescribed burning of buttongrass, for 2004 (blue line) and 2070 (blue line). Climate scenarios in the model were based on CSIRO's climate predictions for the year 2070 (Source: Karen King, Bushfire CRC, unpublished data)



Fire frequency in moorland habitats is an underlying determinant of species richness and diversity. Frequent fires ensure the long-term survival and abundance of buttongrass species. A reduction in fire frequency to more than 50 years could result in successional change to teatree scrub (Marsden-Smedley & Kirkpatrick 2000).

The issue of soils and their susceptibility to climate change effects is also important. There is potential for changes in fire frequency (either from uncontained wildfires or increased management burns) to affect the existing organic soils in the Tasmanian Wilderness. Organic soils are associated with a range of vegetation types, including buttongrass moorland, rainforest and sphagnum bogs. Changing fire regimes will have a direct impact on the flora of these communities; further research is needed of the effect that loss of organic soil horizons would have on the potential for the communities to re-establish, and of the impact of the loss of the soil on the Tasmanian Wilderness' geoheritage value (Tasmanian Department ofPrimary Industries and Water, pers. comm.).

Fire regimes that sustain buttongrass moorland habitats are important for a range of fauna that are closely associated with this vegetation type. For example, the critically endangered orange-bellied parrot (*Neophema chrysogaster*) is highly dependent on buttongrass moorland habitats for their survival (Marsden-Smedley 1993). However, changed fire regimes as a result of climate change are likely to be detrimental to many species, prompting the need to investigate the relationship between extreme fire events, and implications for species abundance and distribution (K King 2006, pers. comm.). According to Parks and Wildlife Service (2004), 'increases in fire frequency have resulted in buttongrass moorland replacing some *Sphagnum* peatlands in parts of the Wild Rivers National Park'. Excessive loss of organic peat soils through erosion has been attributed to frequent burning of buttongrass moorlands. The potential impact on water quality from these erosion events is yet to be determined (Tasmanian Department of Primary Industries and Water, pers. comm.).

Buttongrass moorland. *Nicola Bryden and the Department of the Environment, Water, Heritage and the Arts*

Because buttongrass moorlands are considered to be highly flammable (Pyrke & Marsden-Smedley 2005), they pose a major fire management issue for park authorities. High fuel loads increase the probability of fire burning beyond the buttongrass moorland boundary and into teatree scrubland where there is a greater potential for initiation of peat fires (Marsden-Smedley & Kirkpatrick 2000). Based on field observations, it would appear that buttongrass has become much drier since the 1980s (J Balmer 2006, pers. comm.), with large areas of buttongrass that have remained unburnt for many years (Marsden-Smedley & Kirkpatrick 2000). A major dilemma for managers is how to develop an appropriate fire management strategy that will address the need for fuel reduction while at the same time ensure the long-term conservation of biodiversity values.

The impact of burning on peat accumulation and the impact of fire on the rate of spread of *Phytophthora cinnamomi* is unclear. Biodiversity is enhanced immediately after fire in some buttongrass moorlands in areas with higher nutrient capital, but is slow to recover in areas of low nutrient value. Few species are restricted to young vegetation types but some do decline in abundance over time. Succession is not a major issue, because the succession time is very long and the extent of the vegetation type vast. The major debate is to whether burning of moorlands will significantly reduce the risk of fires running into alpine and rainforest communities during summer wildfires. Some burning is needed for habitat maintenance, but not nearly as high a frequency as would be required for hazard reduction purposes (Tasmanian Department of Primary Industries and Water, pers. comm.)

Animal species of conservation significance (broad-toothed rat) and examples of evolution in mainland mammals (e.g. sub-species of Bennett's wallaby, swamp antechinus, southern brown bandicoot, common wombat, common ringtail possum, common brushtail possum, and *Dasyurid* spp.

A decline in snow cover has been reported for the Australian Alps (Whetton 1998) as well as overseas (Houghton et al. 2001). Snow cover is likely to continue to decrease in the Australian Alps in response to warmer temperatures (Hennessy et al. 2003). Tasmania will also experience a reduction in snow cover, with current estimates predicting a 10–40% reduction by 2020 (Hennessy et al. 2003). In Australia, few studies have investigated the effects of changes in snow cover on the distribution and ecology of small mammals (Sanecki et al. 2006). However, research conducted overseas has shown that snow plays an important role in the ecology of many alpine organisms (Stenseth et al. 2004) by providing thermal insulation against lower temperatures (Merritt & Merritt 1978). Although snow cover can ameliorate the effects of cold weather on small mammals, research conducted in the Kosciuszko National Park in the Snowy Mountains has also revealed that species respond differently to snow cover (Sanecki et al. 2006). For the Tasmanian Wilderness, snow cover is not really a crucial factor, because snow cover is generally of limited cover and extent during the winter months.

The relationship between seasonality changes and reproductive success (particularly with respect to male-biased sexual size dimorphism) in mammals as well as macropods is well documented (Issac 2005). A study conducted mainly outside of the Tasmanian Wilderness has revealed sufficient evidence to suggest that both drought and temperature can have a significant impact on the reproductive success of Bennett's wallaby (*Macropus rufogriseus*) (Driessen 1992).

Endangered bird species (e.g. orange-bellied parrot, ground parrot).

A climate-induced change in fire characteristics (more frequent, widespread and intense) could threaten the survival of many of the World Heritage area's bird species through a loss of core habitats. However, fire is also essential for the maintenance of buttongrass moorland communities and hence the habitat of the orange-bellied parrot (*Neophema chrysogaster*) (Driessen 1999; Marsden-Smedley 1993). The buttongrass moorlands, for example, provide a readily available food source (e.g. fruit and seeds) for the critically endangered orange-bellied parrot (*Neophema chrysogaster*) (Brown & Wilson 1984). As the south-west region of Tasmania is now the only breeding habitat for this migratory bird, the Tasmanian Wilderness has important conservation significance for this species (Parks and Wildlife Service 2004). The buttongrass moorlands are also the primary habitat of the ground parrot (*Pezoporus wallicus*), and therefore a climate-induced change in fire regime could also threaten the survival of this species. In south-western Australia, a combination of land clearing and a changed fire regime has already led to a decline in population numbers of the ground parrot (Gill et al. 1999).

Endemic members of invertebrate groups (e.g. Anaspidacea, Parastacidae, Phreatoicidae). Invertebrates of unusually large size (e.g. the giant pandani moth, *Proditrix* sp., several species of Neanuridae, the brightly coloured stonefly (*Eusthenia spectabilis*)).

The Tasmanian Wilderness has a high level of endemic invertebrates with a majority of their range confined to the property. These include species from families Oligochaeta, Gastropoda, Amphipoda, Isopoda, Anaspidacea and Decapoda. The rainforests of the area provide an important habitat for a range of endemic invertebrate species including the pandani moth (*Proditrix nielseni*), the pencil pine moth (*Dirce aesiodora*), stag beetles (*Lissotes*) and moss beetles (*Pedilophorus*) (Mallick & Driessen 2005). However, to date, population numbers of most insect species have not faced any significant threat from environmental change (M Driessen 2006, pers. comm.). The pencil pine moth was previously listed as a vulnerable species under the Tasmanian *Threatened Species Protection Act 1995*, but has since been withdrawn.

The buttongrass moorlands provide an important habitat for many primitive and endemic invertebrates including two syncarid crustaceans *Allanaspides hickmani* and *A. helonomus*, as well as the rare dragonfly species *Synthemiopsis gomphomacromioides*. The impact of climate change on *Allanaspides* spp. is considered in Driessen et al. (2006) and Driessen and Mallick (2007). The important symbiotic associations between invertebrates, and buttongrass moorland and peatland vegetation communities, are well known. The burrows created by the peat burrowing crayfish (*Parastacoides*) provide an available source of oxygen and water for many plant species living in association with buttongrass moorlands communities.

Skinks including skinks in the genus Niveoscincus. Pedra Branka skink (*Niveoscincus palfreymani*) and southern snow skink (*Niveoscincus microlepidotus*).

The Tasmanian Wilderness has three endemic alpine skinks: the mountain skink (*Niveoscincus orocryptus*), the northern snow skink (*Niveoscincus greeni*) and southern snow skink (*Niveoscincus microlepidotus*). These cold-adapted endemic species are mainly confined to the high alpine mountain peaks of the area. Another skink species with restricted range is the Pedra Branca skink (*Niveoscincus palfreymani*). The habitat of the Pedra Branca skink is confined to an isolated rock island, Pedra Branca, situated 26 km off the south-east coast of Tasmania. This island contains around 250 individuals and lies within the boundaries of the Tasmanian Wilderness.

The effect of temperature on embryonic development (Shine & Harlow 1993) and on phenotype (Shine & Harlow 1996) has previously been demonstrated in live-bearing (viviparous) lizards. The effects of temperature on reproduction in reptiles have also been discussed previously in this report. However, to date, few studies have examined the effects of environmental change in *Niveoscincus* species. Wapstra (2000) reported on the effects of environmental change on embryonic development in the viviparous scincid lizard *Niveoscincus ocellatus*, an endemic species of Tasmania. The results of this study provided evidence for the importance of external temperature in determining neonate phenotype, gestation time and embryo development. Girling et al. (2002) also examined the complex interactions between temperature and parturition in viviparous skink species (southern snow skink (*Niveoscincus microlepidotus*), and the metallic skink (*Niveoscincus metallicus*)) and found that warmer temperatures (22 °C and 28 °C) increased birthing time.

Higher temperatures have been shown to promote body size and reproductive output in the common mountain lizard (*Lacerta vivipara*) that inhabits the high mountain regions in southern France (Chamaille-Jammes et al. 2006). However, this study also highlighted a discrepancy between habitat and individual-based predictions. Although they concluded that increased temperatures had a positive effect on individuals, their habitat is likely to disappear as a consequence of the higher temperatures. According to Chamaille-Jammes et al. (2006: 400), '*suitable habitats of common lizard in the study region, at the southern margin of species distribution, are likely to disappear, and have probably shrunk. However, the factor driving this decline-increase in temperature had only positive effects on individual fitness. Both individual- and habitat-based approaches are necessary to fully understand species' response to climate change*'.

Although these studies illustrate the effects of temperature on fecundity and physiology on lizard populations, it is difficult to draw any conclusions as to what impact future climate change will have on these species. Due to their restrictive habitat range and limited dispersal ability, some researchers believe that global warming may lead to the extinction of high-altitude skinks in the Tasmanian Wilderness (M Driessen 2006, pers. comm.). A similar forecast has also been made for some high-altitude species of the *Sphenomorphus* group of lygosomine skinks in New Guinea (Greer et al. 2005).

Indigenous families of frogs with Gondwanan origins.

The Tasmanian Wilderness contains several frog families with Gondwanan origins (e.g. Tasmanian froglet *Crinia tasmaniensis*, brown froglet *Crinia signifera*, Tasmanian tree frog *Litoria burrowsae*, brown tree frog *Litoria ewingi*). Very little is known about the impacts of climate change on these families of frogs. The causes of global amphibian decline are complex, including pathogen outbreaks (primarily chytridiomycosis in Australia, but the status of chytrid infection in wild Tasmanian frog populations is unknown), changes to precipitation and available moisture, climate change impacts such as warmer water temperatures, and possibly UV-B exposure (Häder et al. 2002). Tasmania has been exposed to significantly increased UV-B exposure as a result of ozone depletion than other parts of Australia. A range of negative effects on amphibians of UV-B radiation have been recorded, such as damage to skin and eyes, and reduced hatchling growth success. Even though the causes of ozone depletion and global warming are distinct, their impacts can interact negatively. For example, climate-induced reductions in water depth at sites where eggs are laid have caused high mortality of embryos due to increased exposure to solar UV-B radiation and subsequent vulnerability to infection (Häder et al. 2002). A wider discussion on the potential impacts of climate change known in relation to amphibians is provided elsewhere in this report.

Coastal plant communities free of exotic sand-binding grasses, which show natural processes of dune formation and erosion. The south and south-west coasts comprising steep headlands interspersed with sweeping beaches, rocky coves and secluded inlets.

Rising sea levels and large storm-surge events pose a significant threat to the integrity of the Tasmanain Wilderness coastline. These threats are likely to result in physical changes (erosion, rockfalls and slumping) to the coastal zone, dramatically changing the geomorphology of coastal regions (Sharples 2006). In addition, these coastal effects can significantly impact on coastal terrestrial environments, as well as marine habitats and the biota they support (Edgar et al. 1997).

Over the past couple of years, managers have noticed a substantial increase in the extent of beach erosion (M Pemberton 2006, pers. comm.). According to the Tasmanian Department of Primary Industries and Water (pers. comm.), '*many beaches are showing signs of recession at rates faster than earlier last century*'. However, there is no conclusive evidence that links this observation with rapid climate change. Coastal dunefields may be a useful indicator of climate change. Changes in the type and orientation of dunes may shed some light on both destabilisation of foredunes and changes in wind regime (Tasmanian Department of Primary Industries and Water, pers. comm.).

Recent work suggests that there was no significant increase in storminess last century (Zhang et al. 2000) and that widespread beach erosion is primarily attributable to rising sea levels (Zhang et al. 2004). As sea levels rise, beach systems will shift landwards in response (Nichols 1999). A consequence of sea level rise is an increase in flooding of low-lying areas. Certain landforms (e.g. 'soft' shorelines) are particularly vulnerable to rising sea levels and severe storm-surge events (Sharples 2006). A 1:25,000 scale map of the Tasmanian coastline has been constructed specifically for the identification of shoreline types. Sharples (2006) identified several coastal types vulnerable to the effects of climate change. These include:

- soft, muddy estuarine and deltaic deposits
- sandy shorelines
- colluvial shores [39]
- rocky shorelines.

Coastal ecosystems are also an important part of the World Heritage values. With rising sea level, the depth of water above subsurface vegetation communities will increase, almost certainly resulting in further reduced available light. Die-off will result, starting at the deeper boundaries of the communities. A specific example is Bathurst Channel, Bathurst Harbour and Melaleuca Inlet, which are dominated in the surface layers by highly tannin-stained freshwater, with a saltwater wedge extending into much of the system. The tannin staining has the effect of greatly reducing light penetration. As a result, much of the system has bare sediment below depths of 1–2 m, as photosynthetic plants are unable to tolerate the low light conditions. However, the system has numerous extensive shallow bays (off Bathurst Channel and Bathurst Harbour), which have wide subsurface vegetation communities around their shorelines and, in cases, across the whole floor of the harbour. The total area of subsurface vegetation is extensive and much or all of this may be impacted by rising sea levels. A number of possible consequences of sea level rise would benefit from investigation, in particular:

- the potential for communities to colonise inundated land (much of the system is rock fringed and opportunities may be limited)
- the loss of photosynthetic plant input into the ecology of the system—with impacts on invertebrates, fish and birds
- mobilisation of subsurface sediments due to loss of plant cover (Tasmanian Department of Primary Industries and Water, pers. comm.).

39 Colluvial shores are made of loose bodies of sediment deposited or built up at the base of a slope.

Impact on cultural values

Cultural criteria

Criterion (iii): To bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared.

Criterion (iv): To be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history.

Criterion (v): To be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change.

Values include:

Archaeological sites that provide important examples of the hunting and gathering way of life.

Coastal erosion processes along the south-west coast of the Tasmanian Wilderness pose the main threat to Aboriginal heritage sites. The Tasmanian Parks and Wildlife Service, and the Department of Primary Industries and Water, have invested in a stabilisation program for the protection of several large Aboriginal midden sites. A number of Aboriginal heritage sites have been lost as a result of extensive erosion processes.

Cave systems and sinkhole environments contain many supported values such as cave ecosystems, palaeontological deposits, and Aboriginal cultural values such as Pleistocene cave art, midden and hearth deposits. Effects on cave ecosystems and specialised component species warrant consideration, as changes in the physico-chemical composition of karst groundwater may affect sensitive cave-adapted fauna. Changes to cave microclimates are known to affect the preservation of cave art; there is some potential for cave microclimates to be altered in response to external changes in temperature and relative humidity. Palaeontological deposits—often consisting of bone deposits from extinct species such as *Sthenurus, Diprotodon*, etc.—are similarly susceptible, as their preservation relies on maintenance of ideal microclimatic conditions.

8.5.4 Associated threats

Dieback from *Phytophthora cinnamomi* continues to be a major problem in the Tasmanian Wilderness; the impact of climate change on rates of phytophthora spread is not known. Extensive river erosion from commercial boating activities in parts of the area, such as the Gordon River, is likely to interact negatively with the additional erosion problems from sea level rise, although sea level rise may also assist the preservation of the meromictic lakes beside the Gordon River. Although to date there has been no successful establishment of new animal species in the Tasmanian Wilderness and feral goats have been eradicated, the degree of threat posed by the recent apparently successful establishment of the fox (*Vulpes vulpes*) in northern Tasmania—and the implications of climate change for the rate of spread, degree of establishment and ultimate impact of this major predator on the values of Tasmanian Wilderness—is unknown but likely to be significant. Tasmania still maintains the last extant wild populations of a number of species, particularly small to middle-weight mammals such as a variety of bandicoots and bettongs, whose extinction or near extinction on the mainland has been attributed to predation by foxes and cats (Burbidge & McKenzie 1989).

There is the potential for changes in fire frequency (either from uncontained wildfires or increased management burns) to impact on the existing organic soils in the Tasmanian Wilderness. Organic soils are associated with a range of vegetation types, including buttongrass moorland, rainforest and sphagnum bogs. Changing fire regimes will have a direct impact on the flora of these communities. Some preliminary work using the FIRESCAPE model suggests that by the year 2070 it will be necessary to almost double the amount of prescribed burning to maintain the area burnt by unplanned fires at the current level. There is very little knowledge of the traditional burning methods used by Tasmanian Aborigines to manage grassland systems. The opportunity to understand the consequences of Aboriginal burning regimes is likely to be lost as the climate continues to change from that in which the Aborigines undertook their burning practices.

World Heritage area viewed from Bruny Island. *Nicola Bryden and the Department of the Environment, Water, Heritage and the Arts*

8.5.5 Gaps in knowledge and future directions

- Further research is required to determine the extent of the risk that climate change poses to ecosystems in the Tasmanian Wilderness, together with identifying management practices that would reduce this risk. There is the need to investigate the relationship between extreme fire events, and implications for species abundance and distribution for buttongrass moorland systems.
- Improving understanding of the susceptibility of soils to climate change effects is important. Further work could beneficially be undertaken on the effect that the loss of organic soil horizons will have on the potential for the communities on organic soils (including buttongrass moorland, rainforest and sphagnum bogs) to re-establish, or on the impact of soil loss on geoheritage values.
- A greater knowledge and understanding of fire regimes is necessary if the management aim is to ensure maintenance of the current ecological mix of plant and animal species. An increased understanding of Indigenous fire management regimes and of pre-human fire history would inform the development of a prescribed burning management plan in the face of climate change. There are aspects of the FIRESCAPE model that need further work, such as the weather conditions and Soil Dryness Indexes under which fire can burn in rainforest and under which it is self-extinguished.
- In 2001–2002, altitudinal transects on Mt Weld were undertaken as part of a long-term climate change study. The site will be surveyed again in 2011–2012 to determine if climate change is having any impact on plant species. Surveys should then continue on a regular basis.
- Little is known about the chemical balancing and changes that are likely to take place in peatland systems, and their biology. The impact of fire on erosion and sedimentation transport should also be examined.
- The future impact of sea level rise on the coastal geomorphology is largely unknown. Systems should be put into place to monitor and measure relevant parameters of coastal erosion (beach recession). According to the Tasmanian Department of Primary Industries and Water (pers. comm.), '*Changes in the type of and orientation of dunes may shed some light on both destabilisation of foredunes and changes in wind regime*'. Although some site-specific modelling and assessment of coastal erosion mechanisms have been explored (Hennecke & Greve 2003), there is an opportunity for future work to be undertaken in the Tasmanian Wilderness.
- Areas not fully covered in this report that would benefit from further research in relation to climate change impacts include:
  - vegetation and organosol regulation of temperature and acidity
  - base level change in coastal and estuarine systems
  - vegetation change and sediment flux
  - temperature and acidity of meteoric waters.[40]

40 Meteoric water is water in the ground that has come from the atmosphere as rain or condensation.

8.6 Gondwana Rainforests of Australia

Boundary between wet sclerophyll forest and sub-tropical rainforest, Lamington National Park. *Paul Candlin*

8.6.1 Climate change scenarios for Gondwana Rainforests of Australia

The following climate change scenarios for this World Heritage property, relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[41]

- Temperatures are expected to rise and the number of hot days to increase. By 2030, the average annual temperature is projected to rise by 1.3 °C ± 0.6 °C.
- In the northern parts of the property, average annual rainfall is expected to fall 3.5% ± 11%, but larger declines are projected for autumn, winter and spring.
- Although average annual rainfall is expected to remain essentially unchanged in the south (0% ± 15%), the seasonality of the rainfall is expected to change with less rainfall in winter and spring, and more rainfall in summer and autumn.
- Higher evaporative demand, due to higher temperatures and less rainfall, will result in less runoff into river systems.
- There is likely to be an increase in the severity and frequency of drought conditions. However, more frequent extreme weather events, leading to increased flash flooding, will occur.
- Sea level is expected to rise by about 17 cm by 2030.[42]

8.6.2 Summary

The Gondwana Rainforests of Australia comprises 42 discontinuous areas within the protected area estate totalling 366,514 ha (DEWHA in press). In this region, between 1950 and 2003, the mean annual maximum temperature and the annual mean temperature increased by 1.5 °C and 1.0 °C respectively. Over the same time period, the annual total rainfall decreased by 75.8 mm (Hennessy et al. 2004). The majority of the World Heritage values in this region are at risk from higher temperatures, drought and a consequential change in fire regimes.

41 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

42 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

There has been no comprehensive research into potential climate change impacts in this region (Chester & Bushnell 2005). It may be possible, however, to draw on experience in the Wet Tropics of Queensland to make some inferences about the potential impacts of climate change on the Gondwana Rainforests. Hunter (2003) identified more frequent and intense fire regimes as a major threat to the integrity of its World Heritage values.

8.6.3 Potential climate change impacts on World Heritage values

Natural values

Natural criteria

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Criterion (x): To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Values include:

Diversity of flora including ancient ferns, tree ferns and conifers.

The Gondwana Rainforests region has an exceptionally rich diversity of primitive plant communities, which are of conservation significance. The forest structure is similar to the Wet Tropics of Queensland, with altitudinal gradients providing a range of microclimatic zones and microhabitats.

There are two groups of Gondwana Rainforests considered to be under particular threat from climate change in the Gondwana Rainforests region: the microphyll fern forests, typically dominated by Antarctic beech (*Nothofagus moorei*) (Taylor et al. 2005); and the simple notophyll evergreen vine forests, generally dominated by *Ceratopetalum apetalum* (coachwood). The latter occur on relatively infertile soils under high rainfall conditions and often form a major component of wet sclerophyll forests. In the Tweed Caldera area they form extensive stands on the Tertiary rhyolites of Nightcap Range, Springbrook, the acid volcanics in Mt Warning National Park and the eastern part of Lamington National Park. Many of the noteworthy plant species endemic to this region (e.g. *Eidothea hardeniana* and *Eucryphia jinksii*) occur in this rainforest type, rather than in the microphyll fern forests (W J F McDonald, pers. comm.).

Nothofagus moorei currently has a limited and disjunct distribution, and is vulnerable to climate change. The species can resist moderate fire but very little seedling regeneration occurs where the frequency of severe fire is too great. If a beech stand is affected by severe fire, fire-tolerant species will invade and beech seedlings do not regenerate. Fire is likely to be a greater issue for those *Nothofagus* populations abutting eucalypt-dominated forests compared with those abutting other rainforest types. Low seedling dispersal is likely to result in more patchiness and eventual disappearance of Antarctic beech (*Nothofagus moorei*) forests because of the limited ability to spread to more suitable climates. However, although *Nothofagus moorei* is at risk from climate change, its ability to reproduce vegetatively may allow it to persist (Taylor et al. 2005), and literature on the species suggests the pattern of change may be more complex than a simple contraction. Schultz (2008) speculates that the southern population of *Nothofagus* may have the potential to increase under climate change—however, this is likely to be negated if fire frequency increases. The associated species in this community, particularly the epiphytic ferns and bryophytes, are most threatened by potential climate change effects such as the increasing basal altitude of the orographic cloud layer.

At the other end of the rainforest spectrum, the dry rainforests are also under threat from climate change. These include the Araucarian vine forests and vine thicket communities, such as those in the Oxley-Wild Rivers National Park. These will be adversely affected by lower and more variable rainfall, increased frequency and intensity of fire in the surrounding landscapes, and the increasing impact of invasive plant species such as *Lantana camara* (W J F McDonald, pers. comm.). The combination of increased frequency and intensity of fire and increasing lantana could also form a deadly feedback loop, as lantana provides heavy fuel loads in dry times, which may drive fire deeper into the rainforest, further increasing the spread of lantana.

Hunter (2003) identified fire to be a major threat to the integrity of the World Heritage values of the Gondwana Rainforests. Rainforest vegetation is particularly sensitive to fire, which is required for normal ecosystem functioning in the majority of locations adjoining these regions. More intense, and more frequent, fires could threaten the rainforests of the property, shifting the boundary between rainforest and sclerophyll forest. The effects of fire on the various forest types are shown in Table 7.

Table 7. The effects of fire on Gondwana Rainforests of Australia vegetation

Forest type	Tolerance
Rainforest	No fire acceptable
Wet sclerophyll forest	Spescies decline expected if successive fires, of any intensity, occur less than 25 years apart or if no fires occur for more than 60 years. Crown fires (fires that burn through the vegetation canopy) should be avoided in the lower end of the interval range.
Dry forest complex	Species decline expected if fires occur at intervals of less than five years, if there are no fires for more than 30 years, or if successive fires occur that totally scorch or consume the tree canopy.
Shrubland/heath complex	Species decline expected if fires occur at intervals of less than seven years, or occur at intervals of more than 15 years.
Grassland/herbfield complex	Some intervals greater than seven years should be included in coastal areas. There is insufficient data to prescribe a definite maximum interval. Evidence indicates the maximum interval between fires should be approximately 10 years.

Source: NSW National Parks and Wildlife Service (2002: 17). After Bradstock et al. (1995).

While some rainforest types are at high risk, others may expand. For example, the contraction of microphyll fern forests may correspond with the expansion of subtropical warm temperate forests (or at least some of the more common subtropical rainforest species) (Schultz 2008; Rob Kooyman, pers comm.). Areas where microphyll fern forests abut subtropical warm temperate forests include Lamington, Mt Ballow and Werrikimbee.

Bird species (logrunner, thornbills, scrubwrens and gerygones, lyrebirds, rufous scrub-bird, bowerbirds and tree-creepers).

The Gondwana Rainforests are an important habitat for the descendants of a primitive group of Corvid birds that include lyrebirds, rufous scrub-birds, bowerbirds and tree-creepers. The rufous scrub-bird (*Atrichornis rufescens*) is endemic to the Gondwana Rainforests and is regarded by some researchers as a good indicator species for rainforest condition (Chester & Bushnell 2005; Ekert 2003). Fire can have a significant impact on rufous scrub-bird populations. An El Niño year, in 2002, was one of the driest and hottest (highest mean maximum temperature) years on record (Hennessy et al. 2004). Fires burnt through extensive areas of simple notophyll, evergreen vine forest, destroying rufous scrub-bird habitats, and reducing male population numbers by more than 60% in the Gibraltar Range and Washpool National Park (Olsen et al. 2003).

Groundcover-dependent species, such as the eastern bristlebird, (*Dasyornis brachypterus*) are also at risk from recurrent fires (Baker 2000). Habitat loss and fragmentation have depleted population numbers, and recent estimates are that only 100 birds remain within the Gondwana Rainforests region (Cavanaugh, pers. comm., cited in Chester & Bushnell 2005). The eastern bristlebird is listed as endangered by the *Threatened Species Conservation Act 1995* (NSW) and the *Nature Conservation Act 1992* (Qld).

Brindle Creek frog habitat, Border Ranges. *Paul Candlin*

An intensive six-year monitoring program has been undertaken for the rufous scrub-bird and a one-year program for the endangered eastern bristlebird (Chester & Bushnell 2005). According to Pyke et al. (1995), populations of eastern bristlebirds can be maintained, providing there is a four to five-year interval between fires. An appropriate fire management strategy will ensure the long-term survival of these endangered bird species. Tolhurst (1996) observed that fuel reduction burning can help in the long-term conservation of many bird species.

Frog species (frogs in the families *Myobatrachidae* and *Hylidae*, species of the relict genera *Assa*, *Lechriodus, Mixophyes* and *Philoria/Kyarranus*, and members of the *Litoria pearsoniana/phyllochroa* complex).

There are numerous papers (e.g. Ehmann 1997; Hines et al. 1999; Hines & McDonald 2000) reporting the decline of several frog species in the Gondwana Rainforests region, including Fleay's barred-frog (*Mixophyes fleayi)* and the giant barred-frog (*Mixophyes iteratus)*. The reason for these declines is unclear, but factors such as disease (chytrid fungus) or combinations of factors, including climate change, have probably contributed (Hines and the South-east Queensland Threatened Frogs Recovery Team 2002). These frog species are listed as endangered in the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*. Queensland's Parks and Wildlife Service has developed a recovery plan for *M. fleayi* and *M. iteratus* (Hines and the South-east Queensland Threatened Frogs Recovery Team 2002). However, there is no recovery plan for stream frogs in Gondwana Rainforests in New South Wales (Chester & Bushnell 2005).

Climate change may be a factor in the world-wide decline in amphibian populations. The impacts of environmental change on amphibian populations are well documented (Blaustein et al. 1994; Blaustein et al. 2001). Amphibians are among the world's most threatened vertebrate taxa, and nearly one-third of the 6,140 species are threatened with extinction (Stuart et al. 2004). Population declines have been particularly severe since 1980, with measured rates of extinction up to 90 times higher than the background rate over the previous five centuries (Stuart et al. 2004). There is compelling evidence that the causal agent is a fungal pathogen (*Batrachochytridium dendrobatidis*) that infects the keratinised epidermis of amphibians causing the potentially lethal disease chytdridiomycosis (Berger et al. 1998; La Marca et al. 2005). Several studies link global climate change with amphibian population decline (Kiesecker et al. 2001; Pounds et al. 2006) and with the pathogen (Laurance 2008; Wake and Vredenburg 2008). Climate change may make the frogs more vulnerable to the pathogen. There is no bioclimatic model for chytridiomycosis, but such a model would be a valuable tool for assessing whether climate change is likely to affect the potential geographic spread of this disease. However, it may be that even if the pathogen is not favoured by climate change, vulnerability of amphibians to the pathogen may be increased as a result of increased stress as a result of climate change.

Climate change introduces additional pressure on a group already under great threat, and population resilience is the prime issue. As a management approach to climate change, the objective should be to limit the impacts, but unfortunately there is no clear indication of what these may be for amphibians. The critical issue is to understand the sensitivity of amphibians (physiological tolerances) and their adaptive capacities (genetic and phenotypic). The fact that several Gondwana Rainforest endemic amphibians occur at high altitude and are ecological specialists implies that they are sensitive to temperature and moisture regimes. How well they may adapt to rapid climate change is unknown. When undertaking monitoring, target areas should include the ecotones (i.e. the transitional zone between two different habitats) at the extremes of bioclimatic variables (M Mahony, pers. comm.).

In summary, climate change is not considered by most amphibian biologists to be the proximate cause of the catastrophic declines of the past 30 years, although it is suspected to play a role. Amphibians are considered to be accurate indicators of environmental health (Blaustein & Wake 1995) and their disappearance can lead to cascading effects that reverberate through ecosystems (Whiles et al. 2006). Frog species belonging to the genera *Philoria/Kyarranus* and *Assa* are highly susceptible to changes in environmental conditions, and would therefore be excellent indicator organisms for climate change (Seymour et al. 1991). However, the environment of these amphibians is not thought to have changed markedly since 1980 and their decline has been attributed to be most likely due to virulent invasive disease (M Mahony, pers. comm.).

Australian research has focused primarily on the taxonomy and evolution of frog fauna, with little emphasis placed on human-induced changes to the environment and their impact on frog population numbers (Hazell 2003).

Amphibians exhibit a diverse array of breeding strategies. Endemic stream and pond breeders, ephemeral pond breeders, one with parental care, and others that construct nests in the forest floor, all occur in the Gondwana Rainforest. These latter species (*Philoria* spp.) are particularly vulnerable to climate change. As soil moisture decreases, the habitat of these species will become increasingly restricted. Several species of *Philoria* occur only in a small number of locations at high altitude in the Gondwana Rainforests. Seymour et al. (1991) discussed the physiology of the embryonic and larval stage development for this genus (M Mahony, pers. comm.). Future monitoring programs should extend beyond the stream environment to include other endangered frog species in the Gondwana Rainforests (H Hines, pers. comm., cited in Chester & Bushnell 2005).

Reptiles (leaf-tailed gecko, *Saltuarius swaini* and angle-headed dragon, *Hypsilurus spinipes*.).

The North Coast leaf-tailed gecko (*Saltuarius swaini*) is found in a diverse array of habitats ranging from notophyll rainforest to moist sclerophyll forest. This species also inhabits a range of elevations from sea level to over 1,000 m ASL. Its wide climatic distribution suggests this species would adapt to a moderate change in temperature. However, the Tyron's skink (*Eulamprus tryoni*) and the beech skink (*Pseudemoia zia*) are only found above 800 m ASL, so would probably be affected by a moderate rise in temperature as their climatic envelope disappears off the top of the mountains.

Mammals, including monotremes and marsupials.

The Gondwana Rainforests are highly fragmented with only a few corridors of natural vegetation facilitating the movement of wildlife between World Heritage reserves. Many Gondwana Rainforest vertebrate species may experience a contraction in their core habitat due to climate change. They may not be able to migrate to other regions if there is inadequate connectivity between reserves (B Ness, R Kitching 2006, pers. comm.). Animals with low dispersal capabilities are probably at greatest risk from habitat loss, because they are often restricted in their ability to cross safely from one forest isolate to another (Laurance 1990). Cox et al. (2003) investigated the impacts of habitat fragmentation on non-flying mammals of the Eastern Dorrigo Plateau, adjacent to the Gondwana Rainforests. This revealed that the larger mammals are more vulnerable to habitat loss in small remnant habitats, and that individual species respond differently to habitat change, depending on the extent of their specific habitat specialisation (Bentley et al. 2000; Cox et al. 2003).

Studies of the effects of habitat fragmentation and contraction on vertebrate species assemblages have focused primarily on the effects of land clearing (Kavanagh & Stanton 2005). There has been no extensive research in the Gondwana Rainforests of the effects of climate change on vertebrate habitats. Climate change and extreme weather events may exacerbate the current impacts associated with habitat fragmentation and lead to further contractions in existing habitats (Ewers & Didham 2005). In addition, small, relatively narrow reserves are likely to present a greater risk to endemics under future climate change scenarios. A higher risk of extinction of rainforest endemics in the smaller reserves is likely, especially in reserves with a more fragmented shape, a factor that would become increasingly important if the rainforest contracts due to human-induced climate change (Williams & Pearson 1997).

The Gondwana Rainforests of Australia was originally defined by geography rather than by biological diversity (R Kitching 2006, pers. comm.). It should be expanded to include other areas with unique biodiversity value within the broader region. This may also help in the conservation of some endemic species faced with loss of core habitats resulting from climate change. The biodiversity values at most risk from climate change are plant and animal species already faced with the likelihood of extinction from a range of factors, such as land clearing and feral animals. Marsupials of Gondwanan origin considered to be at most risk from climate change include the brush-tailed phascogale (*Phascogale tapoatafa*), common planigale (*Planigale maculata*) and eastern pygmy possum (*Cercartetus nanus*). Although these species are listed in the Lower Risk category on the World Conservation Union's (IUCN) Red List (Chester & Bushnell 2005), their numbers have declined by as much as 50% over recent years (Maxwell et al. 1996).

Species such as the broad-toothed rat (*Mastacomys fuscus*) and the Hastings River mouse (*Pseudomys oralis*) are currently listed as endangered under the *Threatened Species Conservation Act 1995* (NSW). Broad-toothed rat populations have declined and their habitats have also become highly restricted in recent years (Chester & Bushnell 2005). The rufous bettong (*Aepyprymnus rufescens)* is listed as vulnerable under the *Threatened Species Conservation Act 1995* (NSW). This small marsupial inhabits the grassy understorey of open woodland and forests, and is highly vulnerable to predation by foxes and other feral animals (NPWS 2000). More intense and frequent fire regimes likely to occur under climate change could also threaten the relative abundance and survival of these endangered or vulnerable species. The Spotted-tailed quoll (*Dasyurus maculatus*) is also listed as endangered, with population numbers declining significantly due to anthropogenic effects.

Invertebrates (freshwater crays, land snails, velvet worms, mygalomorph spiders, flightless carabid beetles, bird-wing butterflies and glow-worms).

Little is known about the impacts of climate change on invertebrates in the Gondwana Rainforests. There are also significant gaps in the knowledge of higher invertebrate taxa including hydrobiid freshwater snails, land snails, terrestrial leeches, land planarians and *Platyhelminthes* generally, millipedes, and the cricket (weta) families *Anostostomatidae* and *Rhaphidophoridae*. Even the composition and distributions of such conspicuous invertebrate groups as bees (Apoidea) are poorly known in montane rainforests (Williams 2002). Although considerable effort has been made to collect information on butterflies and jewel beetles (Buprestidae), there is little published data (Williams 2002). Invertebrate fauna of conservation significance include the Richmond birdwing butterfly (*Ornithoptera richmondia*) and the freshwater crayfish (*Euastacus jagara*). The freshwater crayfish is confined to the Gondwana Rainforests and has only been identified at a remote location near Mt Mistake. These species are particularly vulnerable to climate change impacts due to their restricted range and distribution (H Hines 2006, pers. comm.).

Although little is known about the impact of climate change on invertebrates in the Gondwana Rainforests, several studies have reported on the effects of climate change on invertebrate populations in other regions (Beaumont & Hughes 2002; Hill et al. 2002; Parmesan et al. 1999) including the extinction of the butterfly species *Euphydryas editha bayensis* (McLaughlin & Hellmann 2002). Insects that are capable typically respond to climate change by migrating to more climatically favourable regions, rather than face the prospect of extinction or adaptation in situ (Hill et al. 2002). For example, European butterfly species have recently shifted their distribution in the direction of the north pole in response to global warming (Parmesan et al. 1999). No such observations have been published for Australian butterfly species. However, Beaumont and Hughes

(2002) identified 77 butterfly species endemic to Australia with wide climatic ranges in comparison to other invertebrate taxa. Many species could be at risk from a moderate rise in temperature of 0.8–1.4 °C (Beaumont & Hughes 2002).

There are several endemic *Trapezitine* butterfly genera that are restricted to the Gondwana Rainforests region, including *Anisynta*, *Hesperilla*, *Mesodinia*, *Motasingha*, *Pasma*, *Signeta* and *Trapezites. Trapezites genevieveae* is restricted to the old-growth rainforest in the region (Williams 2002). The Richmond bird-wing butterfly (*Ornithoptera richmondia*) is confined to the northern sector of the Gondwana Rainforests and its range has undergone considerable contraction since European settlement (Williams 2002). The ability of a species to undergo a change in its distribution will depend to a large extent on its ability to migrate (Beaumont & Hughes 2002; Kitching et al. 1999) and the availability of host plants. Species such as *Trapezites* and groups such as lycaenids (e.g. *Pseudalmenus chlorinda*) identified in Beaumont and Hughes' (2002) study, have limited dispersal capabilities and narrow climatic ranges. They are therefore likely to be vulnerable to future climate change impacts—as is the Richmond bird-wing butterfly, the young of which are dependent on one of two species of the *Aristolochia* vine. The disjunct nature of the Gondwana Rainforests means that the species have to cross significant areas of hostile environment to reach the next rainforest 'island' (Hunter 2009, pers. comm.).

Climate change is being observed to interfere with butterflies' life history stages. The time of spring emergence is controlled by day length, temperature and moisture. Richmond bird-wing butterflies are now hatching over a much longer period and their densities at any one time are low, which impacts on their ability to find a mate (D Sands, pers. comm.). Declines in rainfall are also affecting the ability of plants to produce the soft, young leaves required by the butterfly larvae. This is also impacting on the numbers of leaf-eating beetles such as the chrysomelids (D Sands, pers. comm.).

Changed fire regimes may also be a determining factor for the distribution and adaptive capacity of many invertebrate species in a changing climatic environment. Fire studies show that some species are more vulnerable to the effects of frequent, but low-intensity, fire regimes, while others may benefit from more frequent fires. In general, insect larvae, flies and beetles appear to be adversely affected by frequent burning, whereas, bugs, ants and spiders are less affected, and in some cases would appear to respond positively to an increase in fire frequency (York 1996).

Caldera of the Tweed Shield volcano.

A very low climate change impact is expected for the caldera of the Tweed Shield volcano. Rates of rock weathering in response to climate change have not been determined.

8.6.4 Associated threats

Exotic plant species and feral animals pose a significant threat to the integrity of the Gondwana Rainforests' heritage values. Fox predation of vulnerable animal species, such as the rufous bettong, is of concern. Recent discovery of cane toads at Border Lookout (next to *Nothofagus* forest) in the eastern Border Ranges National Park indicate that this invasive species has penetrated into the National Park. The route of entry and dispersal is not known, and potential breeding sites are not identified. Warmer and drier conditions associated with climate change are likely to favour this species (M Mahony, pers. comm.).

8.6.5 Gaps in knowledge and future directions

There has been little long-term research of the impacts of climate change on the World Heritage values of the Gondwana Rainforests (R Kitching, B Ness 2006, pers. comm.). Systematic ongoing monitoring is crucial for assessing long-term climate change impacts on species, as well as on ecosystem dynamics (R Kitching, pers. comm.).

A new project, 'Biodiversity at the Heights' (BATH), commenced in 2007, involving 40 world-leading ecologists. This project will attempt to more clearly define and understand the patterns of biodiversity change along altitudinal gradients ranging from open notophyll vine forest (350 m ASL) to the *Nothofagus moorei*-dominated forests at 1,300 m ASL. This will provide researchers with a calibrated climate change measurement tool, which could also be adapted and applied to other World Heritage sites, such as the Wet Tropics of Queensland (R Kitching 2006, pers. comm.).

Goomoolahra Falls in Springbrook National Park. *Paul Candlin and the Department of the Environment, Water, Heritage and the Arts*

In the context of climate change, the following issues need to be addressed for the Gondwana Rainforests of Australia and its values:

- The rate of vegetation change in response to climate change is unknown.
- Investigation of climate change impacts on fauna and flora should focus on specific indicator species to allow researchers to monitor climate change in a more systematic way. Target areas should be ecotones at the extremes of bioclimatic variables. Indicator species need to be identified. The genus *Nothofagus* is sensitive to environmental change and habitat loss. Species such as Antarctic beech (*Nothofagus moorei*), the rufous bettong (*Aepyprymnus rufescens*), and the stream frog (*Mixophyes fleayi*) are considered excellent indicator species for detecting climate change. However, other researchers note that stream frogs may not be useful indicators of climate change due to the confounding impacts of chytrid fungus and other diseases. The terrestrial breeding frogs (*Philoria* spp.) and the direct developer (*Assa* spp.) may be good indicator species, as both are high-altitude specialists endemic to the Gondwana Rainforests. Neither species is impacted by chytrid fungus because they do not visit streams or ponds. The BATH project will also identify key indicator species.
- Baseline data on species adaptability and vulnerability to environmental change is lacking. There has been little monitoring of targeted fauna or vegetation to detect climate change impacts. This has hampered the ability to accurately model species' responses to climate change. A 'biological information database' of flora and fauna for the north-eastern part of the Gondwana Rainforests region has been established and provides an excellent resource on which to rebuild a strategic monitoring strategy.
- A bioclimatic model of chytridiomycosis should be developed to assist with assessment of the potential geographic spread of this disease.
- A better understanding of species distribution ranges is essential in the development of a management strategy for Gondwana Rainforests of Australia's biodiversity values.
- An appropriate fire frequency is essential for ongoing species survival and habitat maintenance, and fire management strategies should reflect individual species requirements where possible. Vegetation communities, except rainforest, should continue to be burnt in a mosaic pattern to ensure a variable but representative age–class structure in vegetation communities. Managed burning is critical for building natural resilience and resistance to wildfires. Fire should be excluded from highly fragile and erodible areas containing fire-sensitive species.
- More effort in attracting interest from research institutions to undertake routine monitoring, as well as additional funding for weather stations and equipment, is required.

The BATH project is the first step towards addressing some of these issues. It will provide baseline data on species distributions and numbers, as well as providing additional data to help in the refinement of existing predictive models.

8.7 Uluṟu-Kata Tjuṯa National Park

Kata Tjuta Sunset. *Andrew Hutchinson and the Department of the Environment, Water, Heritage and the Arts*

8.7.1 Climate change scenarios for central Australia

The following climate change projections for central Australia, relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[43]

- Climate change scenarios for this region indicate that average annual temperature will increase by 1.7 °C ± 0.6 °C.
- Average annual rainfall is expected to remain essentially unchanged (0% ± 6.5%). However, higher evaporative demand (+5.6% ± 3.1%) will result in less runoff into rivers and streams.
- There will be a tendency for more severe droughts, extreme weather events and flash flooding.

8.7.2 Summary of impacts

Uluṟu-Kata Tjuṯa National Park is located at about 25°05'–25°25'S, 130°40'–131°22'E near the centre of the Australian continent. It occupies an area of 132,566 hectares of arid ecosystems. The most striking landforms, Uluṟu and Kata Tjuṯa, are the large rock formations rising above the sandplains, with Uluru the centerpiece of this unique landscape. This large red sandstone monolith has a circumference of 9.4 km and rises above the flat, sandy plain to a height of about 340 m. The region contains the traditional lands of the Pitjantjatjara and Yankunytjatjara people, collectively known as the Anangu people. Inalienable freehold title has been held by the the Uluṟu-Kata Tjuṯa Aboriginal Land Trust, managed by the traditional owners, since 1985. Management of the National Park is by a Board of Management that includes a majority of Anangu traditional owners.

World Heritage attributes of the property essentially fall into two categories, each of which is likely to be affected quite differently by climate change.

The first category comprises values concerned with Uluṟu-Kata Tjuṯa as a landscape of exceptional natural beauty and scenic grandeur, and illustrating geological processes. Climate change will have some effect on the morphology of the region, including an increase in the spalling of arkose sediments and in cavernous weathering. Those processes are natural, ongoing and directly related to the specific values of the property (Goudie 2003; Sharples 2002; Swart 1994).

The second category is values associated with the property's ecosystem, and the cultural practices and beliefs intimately associated with those threatened ecosystems. The ecological values are likely to be tangibly affected by factors such as wildfires and increased evaporative demand. The nature and intensity of the effects may be contentious.

43 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

8.7.3 Potential climate change impacts of World Heritage values

Impact on natural values

Natural criteria

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Values include:

Uluṟu, one of the largest monoliths in the world, which is affected by erosional processes including sheeting of rock parallel to the surface and granular disintegration known as cavernous weathering; tectonic, geochemical and geomorphic processes associated with the inselbergs of Uluṟu and Kata Tjuṯa which result in the different composition of these two relatively close outcroppings, their differing extent of block tilting and types of erosion, the spalling of the arkose sediments of Uluṟu, and massive 'off loading' of conglomerate at Kata Tjuṯa.

Climate change will have some affect on the morphology of the region, including an increase in the spalling of arkose sediments and in cavernous weathering. Those processes are natural, ongoing and directly related to the specific values of the property (Goudie 2003; Sharples 2002; Swart 1994). As noted above, the specific impact of climate change on the geomorphic aspects of this World Heritage property is unlikely to be readily identifiable in the immediate term, or substantially addressed through conservation measures.

The desert ecosystems and habitat for a wide variety of plant and animal species; and ecosystems and species that show evidence of having been modified and sustained by the land management practices of the Anangu, including the use of fire.

Spinifex grass and low shrubs are the dominant plants in the Uluṟu-Kata Tjuṯa landscape. Although waterholes provide a valuable habitat for a number of rare and unique plant species, more severe and frequent droughts and higher evaporative demand will lead to a reduction in runoff into rivers and streams, and an increased demand on the park's natural aquifers. With less water available for plants and animals, there is a greater probability of an increase in interspecies competition (Dickman et al. 1999).

A change in fire regime (more frequent and intense) may also affect some bird species such as grass wrens and spinifex birds that live in close association with spinifex communities. It is established that a series of wet seasons can result in large unplanned fires (Griffin & Friedel 1985), which in turn can have a profound influence on fire management (Gill 2000). The degree of resilience to changing fire regimes shown by certain plant and animal species may depend upon a range of factors such as dispersal capability; or in the case of perennial plant species, the ability to respond to fire either by seeding or vegetative means (Gill 2000). The distribution and abundance of small mammals has been shown to be driven primarily by high rainfall and fire (Masters 1993). Furthermore, the disappearance of many mammal species has also occurred during periods of long-term drought (Johnson et al. 1989, cited in Masters 1993; Low 1984).

The potential impact of climate change on the plant and animal species that inhabit this landscape is unclear and requires further investigation. The collection of baseline data on species' responses to a range of factors—such as changing fire regimes, rainfall, evaporation and rising CO_2 concentrations resulting from climate change—is warranted (Leavesley 2007, pers. comm.). There is likely to be an increase in pest populations such as the fox (*Vulpes vulpes*), cat (*Felis catus*) and rabbit (*Oryctolagus cuniculus*) (Friedel 1984; Kinnear et al. 1988; Morton et al. 1995). The consequent impact of changes in numbers of these invasive species also needs further investigation.

Uluṟu. *Andrew Hutchison and the Department of the Environment, Water. Heritage and the Arts*

Remarkable and unique natural geological and landform features formed by the huge monoliths of Uluṟu and Kata Tjuṯa set in a contrasting sandplain environment.

Geological formations in the property are stable, relative to dynamic biological systems such as the Great Barrier Reef or vulnerable areas such as the Antarctic ice shelf. Although climate change is unlikely to tangibly impact on the 'exceptional natural beauty' of Uluṟu-Kata Tjuṯa, increased temperatures may deter some visitors, particularly in the hotter parts of the year. Visitations have more than doubled over the past decades and can be expected to show a further increase in coming years, subject to restrictions by the traditional owners on access to those sites. The Board and Director are responsible for future management decisions, in consultation with traditional owners. Control over visitation, and 'hardening' of infrastructure and particular sites, would underpin existing ongoing efforts to maintain and remediate the vulnerable soils of the Gillen land system, including minimisation of erosion and dissemination of invasive flora.

Impact on cultural values

Cultural criteria

Criterion (v): To be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change.

Criterion (vi): To be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance. (The Committee considers that this criterion should preferably be used in conjunction with other criteria).

Values include:

Continuing cultural landscape of the Anangu Tjukurpa which is an outstanding example of a traditional human type of settlement and land use, namely hunting and gathering, that dominated the entire Australian continent up to modern times.

There has been no comprehensive study of potential climate change impacts on Uluṟu-Kata Tjuṯa's ecosystems, cultural practices (e.g. day-to-day hunting and gathering) and beliefs. Much of the literature centres on aspects of particular species or interactions, and arguably there is a need for a more wide-ranging analysis that integrates research into life sciences aspects with cultural questions and communication with the traditional owners of the region (Allan 1997; Allan & Southgate 2001; Borrini-Feyerabend et al. 2004; Dickman et al. 1999; Foran 1984; Griffin & Friedel 1985; Jarman 1986; Kinnear et al. 1988, 2002; Lange & Graham 1993; Masters 1993).

Particular spiritual values, for example, appear to be timeless and the loss of sacred sites can be devastating to a community. Some cultural expression would appear to be directly threatened by climate change; if hunting is a key activity, any substantial reductions in fauna populations associated with climate change will erode cultural values. The likely increase in pest populations of foxes, cats and rabbits (Friedel 1984; Kinnear et al. 1988; Morton et al. 1995) could impact on hunting activities if target species are affected.

Little, if any, work has been undertaken on whether the listed cultural values are under threat from climate change and, if they are, what this could mean for the Indigenous communities that have a role in managing and maintaining the World Heritage values of the park. Research into such implications of climate change and communication between the region's traditional owners, policymakers and scientists (extending the dialogues noted in the Australian National Periodic Report 2002) is desirable.

Management techniques for the property have increasingly reflected the traditional knowledge and priorities of the Anangu, consistent with recognition of the biodiversity consequences of non-traditional fire management regimes and the importance of Indigenous involvement (Allan & Southgate 2001; Borrini-Feyerabend et al. 2004; Gill 2000). Techniques that have supported sustainability of biodiversity through measures such as the creation and maintenance of small-scale water sources, such as rockholes and wells, are appropriate responses to more severe climatic conditions.

The landscape of Uluṟa Kata Tjuṯa is imbued with creative powers of cultural history through the *Tjukurpa*, an Indigenous philosophy expressed in verbal narratives, art and through the landscape itself.

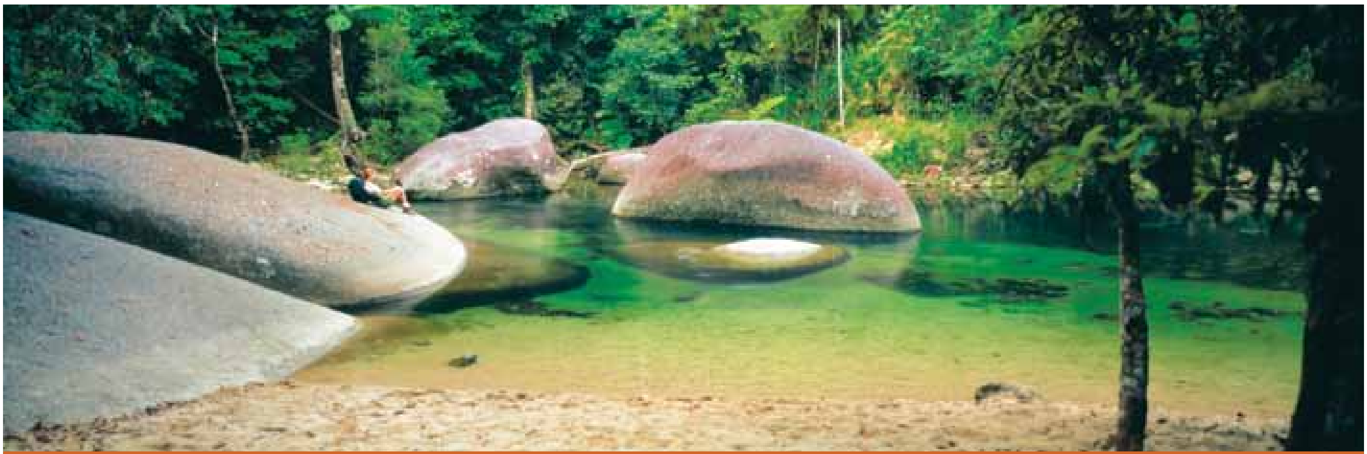
As noted above, some attributes are timeless and appear unlikely to be tangibly affected by adverse climate change. An increase in temperature and a decline in rainfall may pose major problems for some types of cultural sites. The major cultural impact, although one whose significance is uncertain and might perhaps be investigated through the dialogues highlighted above, is the likely reduction of some fauna and consequent erosion of values because Indigenous people are unable to pursue traditional practices.

8.7.4 Gaps in knowledge and future directions

In the context of climate change, the following issues might be addressed regarding Uluṟu-Kata Tjuṯa National Park and its World Heritage values:

- There is uncertainty about future demands on the Uluṟu-Kata Tjuṯa region aquifer, and its capacity to accommodate current or increased tourist numbers and local Indigenous communities, in addition to possible ecological impacts.
- The impact of climate change on Indigenous cultural practice is uncertain and should be explored further.
- The consequent impact on natural and cultural values of changes in numbers of invasive species—such as the fox, cat and rabbit—due to climate change needs further investigation.
- It would be useful to understand the impact of large fire events on animal species and, in particular, the dispersal characteristics of many species (e.g. grass wrens) following a large fire event.
- It would be helpful to develop tools that would assist in understanding and monitoring the impacts of climate change on fire, and determining appropriate management responses. It has been recommended to develop a database of plant and animal responses to fire, and to identify a need to quantitatively map fire spread across the landscape using automated systems (e.g. Landsat imaging at 12 m resolution) (Gill 2000).
- The effects of prescribed burning techniques ('patch' or 'mosaic') on the rate of spread of large fires requires further examination (Gill 2000).

8.8 Wet Tropics of Queensland



The Babinda Boulders south of Cairns. *Tourism Tropical North Queensland*

8.8.1 Climate change scenarios for north-east Queensland

The following climate change scenarios for north-east Queensland, relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[44]

- The average annual temperature for this World Heritage property is expected to increase by 1.3 °C ± 0.6 °C by 2030.
- Annual average rainfall is likely to fall by 3.5% ± 11% by 2030, with particular declines projected for autumn.
- There is likely to be a decrease in annual runoff into rivers, resulting from higher evaporative demand, increased water efficiency by trees due to higher CO_2 and a decrease in annual rainfall.
- Tropical cyclones are projected to increase in number by 10% and to increase in intensity.
- Sea level is expected to rise by about 17 cm by 2030.[45]
- It is unclear how the frequency and intensity of El Niño events will change as a result of global warming (IPCC 2007).
- The severity and frequency of drought is expected to increase.

More recent climate change projections for Australia have been developed by CSIRO (Suppiah et al. 2007). Updated temperature and rainfall scenarios based on these projections are discussed in Wet Tropics Management Authority (2008). These projections do not differ significantly from those presented above.

8.8.2 Summary

The Wet Tropics of Queensland is approximately located between longitudes 15°39'S–19°17'S and latitudes 144°58'E–146°27'E, and covers an area of about 9,000 km^2.

The Wet Tropics of Queensland can expect a warmer, drier future. Although wet season rainfall is likely to increase for most years, this will be countered by an increase in the frequency of El Niño drought years, resulting in reduced wet season rainfall during these periods. More intense rainfall events, including higher intensity cyclones, are likely. Increased temperatures will result in corresponding increases in evaporation and transpiration. Rising sea levels will increase the area of lowlands affected by storm surge, and saltwater intrusion and inundation is expected.

Climate change will have severe adverse impacts on the biodiversity of the Wet Tropics of Queensland. The location and extent of rainforests is largely determined by rainfall and its seasonality, while the type of rainforest and many of the

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44 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

45 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

organisms found within them depend upon narrow temperature ranges. It is predicted that existing ecosystems in the Wet Tropics of Queensland will undergo dramatic changes in species composition or geographic extent, with some likely to disappear entirely. Conversely, some new or novel ecosystems may appear. In general, all native species will be more vulnerable, even those able to tolerate climatic changes per se, as they will all have to deal with a variety of new competitors, predators, diseases and introduced species for which they may have no natural defence.

Climate change has particularly strong implications for the upland sections of the Wet Tropics of Queensland. These cooler parts of the Wet Tropics region provide the only habitat for a diverse and endemic group of fauna and flora, many of which are regarded as 'heat intolerant' and have a narrow climatic range. For example, the buzzing nurseryfrog (*Cophixalus bombiens*) has an annual mean temperature range tolerance of only 1.8 °C, while the average annual mean temperature range tolerance for all endemics is only 5.5 °C.

The upland simple notophyll and microphyll rainforests, which contain the vast majority of the region's endemic fauna, are at greatest risk from climate change, whereas the lowland mesophyll rainforest is most likely to respond positively to an increase in warming. Most of the endemic vertebrates, comprising species adapted to the cooler conditions found above 600 m ASL, will be more vulnerable to climate change impacts through a loss of core habitat.

A predicted rise in the basal altitude of the orographic cloud layer will reduce cloud-stripping—a process that makes a huge contribution to water input in the Wet Tropics of Queensland—place enormous stress on the region's water resources and result in a change to the hydrological regime.

8.8.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criteria

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Criterion (x): To contain the most important and significant natural habitats for in situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Values include:

Large diversity of flora, including ancient taxa retaining primitive characteristics within its ferns and fern allies, cycads, southern conifers and angiosperms; plant species of East Gondwanan origins and relict taxa from Cretaceous angiosperm families.

Yellow Penda buttresses are found only in the Wet Tropics between Cape Tribulation and Mourilyan. *Wet Tropics Management Authority (Queensland)*

The Wet Tropics of Queensland contains one of the most complete and diverse living records of the major stages in the evolution of land plants, from the very first land plants to the pteridophytes, gymnosperms and angiosperms including most of the existing relicts of the forest flora of Gondwana (a super-continent that existed in the southern hemisphere some 200 million years ago) (Goosem 2002).

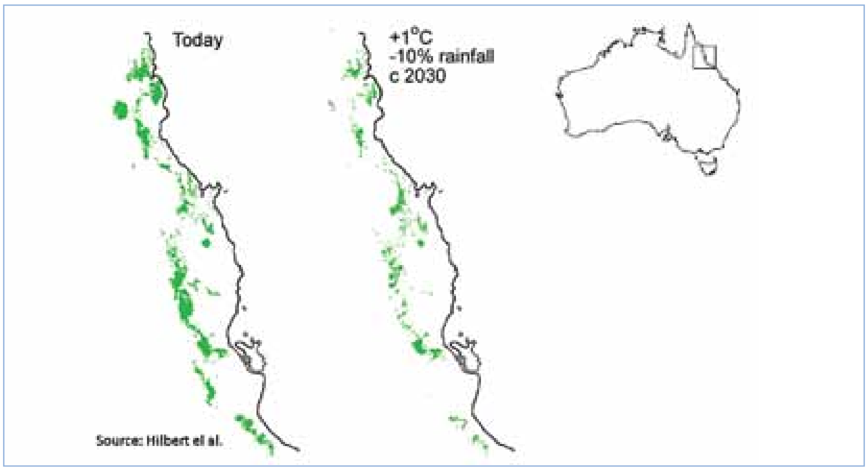
Within the Wet Tropics of Queensland there are over 2,800 known species of vascular plants, representing at least 1,037 genera and 221 families. A total of 75 genera are endemic to Australia and 43 are restricted to the Wet Tropics. Over 700 species are restricted to the region (Goosem 2002). The Wet Tropics of Queensland is second only to New Caledonia in the number of endemic rainforest plant genera conserved per unit area (43 genera and 500 species). Of the endemic genera, 75% are monotypic and none contain more than a few species.

Although accounting for only 0.26% of the total area of the Australian continent, the Wet Tropics of Queensland conserves a large proportion of Australia's plant biodiversity, including: fern species (65%); cycad species (21%); conifer species (37%); orchid species (30%); and vascular plant species (26%) (Goosem 2002).

An examination of past ecological environments has provided an opportunity to model the likely tolerances of various rainforest plant communities to future climate change as well as likely effects on their spatial distribution. Climate records show that during the Holocene period, which occurred 3.6–5 million years ago, the average global temperature was 2.0 °C warmer and the average global annual rainfall was 25% higher than today (Nix 1991). Although higher rainfall would ameliorate the impacts of higher temperatures to some extent, due to an evaporative cooling effect, the Holocene period is regarded as the most appropriate palaeo-model on which to predict future changes in forest distribution patterns and dynamics for this region (Hilbert et al. 2001, 2004; Hilbert & Ostendorf 2001).

The assessment of regional climate change on plant communities for the Wet Tropics of Queensland has consistently used forest structure as the criterion on which to model future responses to climate change, rather than indicator species or species assemblages. Assessment at the species level is simply not practical due to the large diversity and extensive distribution of species (Ostendorf et al. 2001). It has been estimated that a 1.0 °C temperature rise would result in a 50% decrease in the area of highland rainforests by 2030 (Hilbert et al. 2001), as shown in Figure 5. Furthermore, the models indicate that an accompanying increase in rainfall would not ameliorate the effects of temperature rise for this forest type.

Figure 5. Simple notophyll and simple microphyll vine-fern forest distribution—today (left), and in 2030 with a 1 °C rise in temperature and a 10% fall in precipitation (right) (Source: modified from Rainforrest CRC 2003))



For the upland complex notophyll vine forests, the effect of a moderate temperature rise varied depending on the amount of precipitation. However, in contrast to the other forest types, modelling indicates that the lowland mesophyll rainforest is likely to display an expansion in area, and responded strongly to increased rainfall and a 1.0 °C rise in temperature (Hilbert et al. 2001). As expected, the tall open forests and woodlands (wet sclerophyll forests), and medium and low woodlands (dry sclerophyll forests) responded poorly in the models to an increase in rainfall, and were only slightly affected by temperature change. Except for the simple notophyll and mesophyll forests, all modelled forest types exhibit some degree of sensitivity to an altered rainfall regime with only a small to moderate response to temperature increase. The simple notophyll and mesophyll forests responded unfavourably to simulated warming. However, because the pattern of distribution of many species is still largely unknown, and varies significantly depending on soil type and aspect (Goosem 2002), it is difficult to relate these findings back to the impact of temperature and rainfall on individual species.

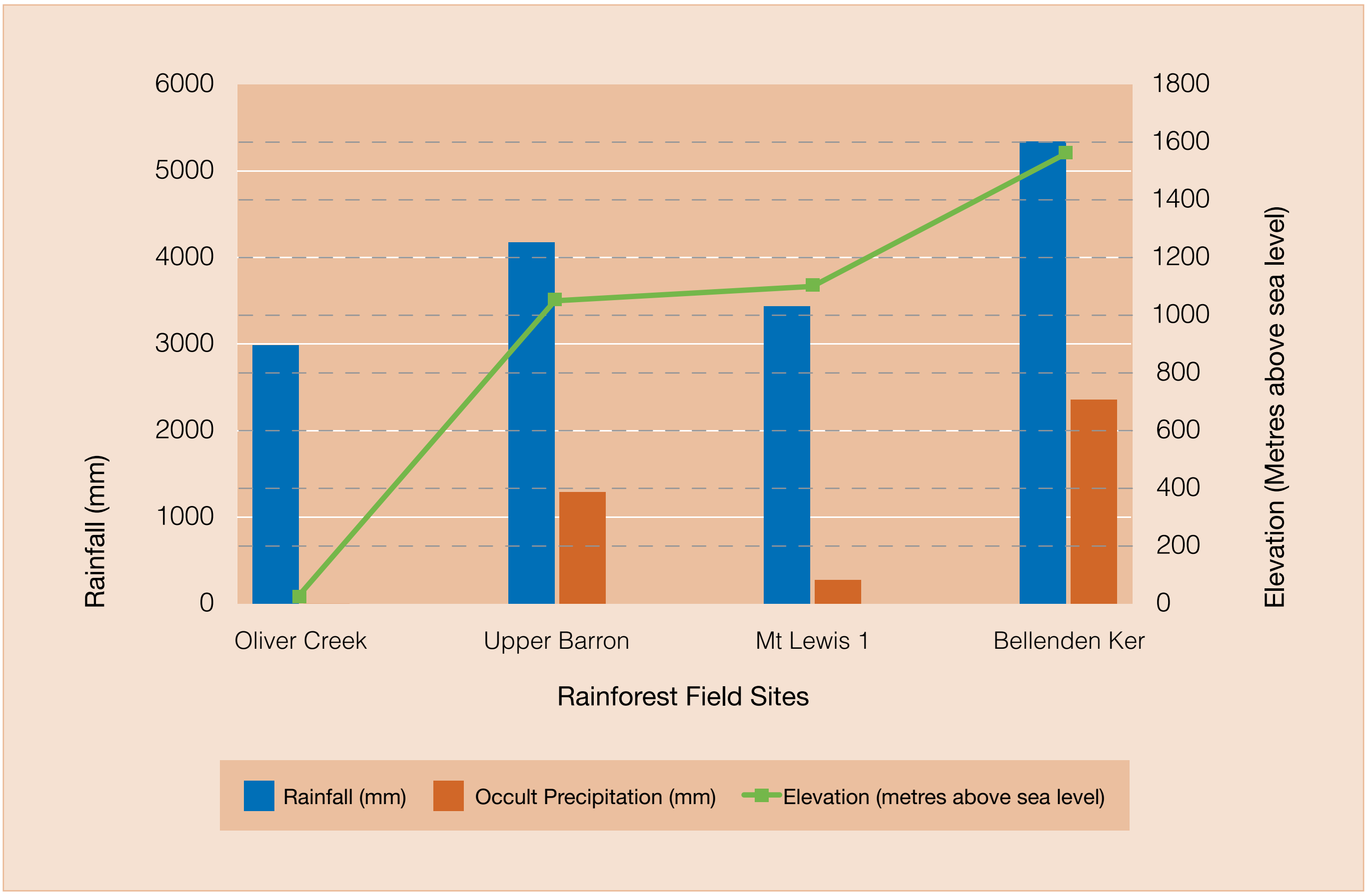
This modelling research suggests that the tropical forests of north Queensland are highly sensitive to climate change likely to occur in the near future within the range (Hilbert et al. 2001) and there is a strong likelihood that the wet tropical rainforest of the Wet Tropics will undergo some climate-related change within the next 30 to 50 years. Furthermore, changes in fire regimes (increased frequency and severity) may lead to changes in the spatial distribution of rainforest and sclerophyll communities. A change in the length of the dry seasons may affect both the timing and sequencing of flowering, leaf flush and fruiting of many plant species. An increase in atmospheric CO_2 levels is likely to affect the nutritional value and toughness of most foliage.

Changes in rainfall and the orographic cloud layer

There is mounting evidence that the altitude of the base of the orographic cloud layer of tropical regions throughout the world could change dramatically in relation to the forests below as a result of continued global warming (Foster 2001; Pounds et al. 1997, 1999; Still et al. 1999). High altitude rainforests that are immersed in cloud for a large proportion of the time 'strip' considerable amounts of moisture from passing clouds in a process also called 'occult precipitation'. The high-altitude rainforests of the Wet Tropics behave like giant sponges, capturing large volumes of water directly from clouds, which they then release slowly throughout the year. This process is considered significant to the overall water budget of the region, especially in terms of water recharge during the dry season. Recent studies have shown that occult precipitation can contribute as much as 30% to the gross precipitation (McJannet et al. 2007) (Figure 6).

A temperature increase of 1.0 °C to 2.0 °C over a 50-year period could result in a rise in the cloud base above the summits of some rainforest mountains, leading to an estimated loss of 70,000 hectares of cloud forest. With 3.0 °C of warming, the altitudes in which cloud stripping occurs is expected to rise from the current 600 m ASL to 900 m ASL, reducing the effective cloud stripping area in the Wet Tropics of Queensland by as much as 40% (McJannet & Reddell 2004). It is expected that a rise in the cloud layer would also place enormous pressure on current water resources and would exacerbate the effects of long-term drought. The resulting loss in the number of species has not been estimated and warrants further investigation.

Figure 6. Relationship between rainfall, occult precipitation and elevation for study sites in the Wet Tropics of Queensland. The percentage of occult precipitation as a percentage of the gross precipitation is shown in brackets (Adapted from: McJannet et al. 2007). With permission of the Rainforest CRC.



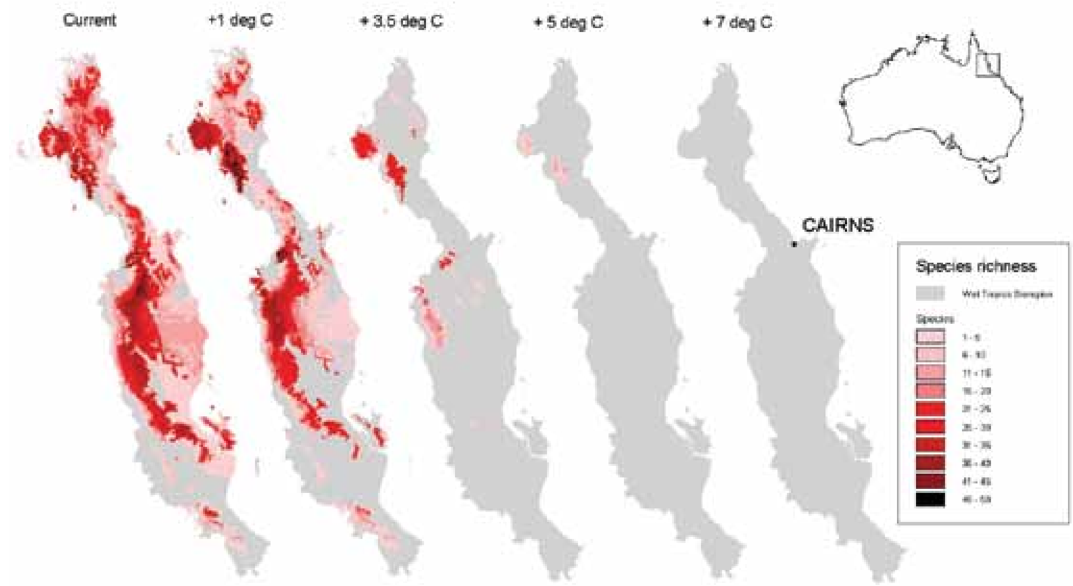
Large diversity of fauna.

The Wet Tropics of Queensland, although accounting for only 0.26% of the total area of the Australian continent, conserves a large proportion of Australia's animal biodiversity, including: 35% of Australia's mammal species (comprising 30% of the continent's marsupials, 58% of its bats, and 25% of its rodents); 40% of Australia's bird species; 29% of Australia's frog species; 20% of Australia's reptile species; 42% of Australia's freshwater fish species and 58% of Australia's butterfly species (Goosem 2002).

Slow-growing palm, Wet Tropics of Queensland. *Wet Tropics Management Authority (Queensland)*

Compared with other World Heritage properties in Australia, the Wet Tropics has one of the most unique and rare collections of vertebrate and invertebrate species in Australia. There are currently 65 regionally endemic species of rainforest vertebrates within an area of 10,000 km^2 (Williams et al. 2003). The majority of the endemic vertebrate species are located in the upland parts of the region particularly above 600 m ASL (Nix 1991). These upland endemic vertebrates have become adapted to the cool, moist environments associated with higher altitudes (Williams & Pearson 1997) and are generally regarded to be intolerant of warmer temperatures (Hilbert et al. 2004). Of the 13 endemic bird species, 10 are highly dependent on cool habitats for their survival and are consequently restricted to higher elevations. Most tropical upland species can tolerate only a very narrow annual mean temperature range. The total loss of core habitats for around 30 endemic Wet Tropics vertebrate species has been predicted with a 3.5 °C increase in temperature combined with variable rainfall (Williams et al. 2003). For the remaining 35 regional endemic vertebrates, an 88.6% loss of their current core habitat distribution is expected (Figure 7).

Figure 7. Loss of species richness for current, +1 °C, +3.5 °C, + 5 °C and +7 °C temperature rise (Source: modified from Williams et al. 2003)



This World Heritage property has the greatest diversification of rainforest frog species in Australia, with core regions of endemism occurring at higher altitudes (McDonald 1992). The areas with the greatest diversity are usually above 600 m ASL (Williams et al. 1996).

Over the past two decades there has been a dramatic decline in frog population numbers in the Wet Tropics of Queensland and, despite extensive field surveys, four primitive species (two from the genus Litoria (*L. nyakalensis* and *L. lorica*) and two from the genus Taudactylus (*T. acutirostris* and *T. rheophilus*)) have not been seen since the early 1990s (Goosem 2002). An association has been made between the incidence of the fungal disease chytridiomycosis (a newly emerging disease that is now considered the most common lethal disease in stream-dwelling frogs) and increased mortality rates of higher-altitude frog populations (Berger et al. 1999; Wet Tropics Management Authority 2005).

Although disease was suggested to be a more likely cause of the dramatic decline in frog population numbers observed worldwide (Berger et al. 1998; Daszak 2003), some international authors report a direct link to a change in global climatic conditions (Pounds 2001; Pounds et al. 2006). Laurance (2008) found that three consecutive years of unusually warm weather (especially high minimum temperatures) appeared to predispose some Wet Tropics highland frog populations to increased vulnerability to virulent pathogens such as the chytrid fungus, suggesting a possible climate change role. It is possible that the range and activity of the pathogen is being enhanced by a changing climate.

Several surviving Wet Tropics frog species are likely to experience a 50% decline in the extent of their core environment as a result of a 1.0 °C temperature rise (Williams et al. 2003). Species with very restricted distributions, such as the Bellenden Ker nursery frog (*Cophixalus neglectus*), and the magnificent broodfrog (*Pseudophryne covacevichae*), are predicted to be highly vulnerable to a 1.0 °C increase in temperature (Williams et al. 2003). Meynecke (2004) also used climate prediction models to simulate the impact of increased temperature and rainfall change on species distribution of the microhylid frogs (*Cophixalus neglectus* and *C. bombiens*). These studies predicted significant range contractions for both species with only a 1.0 °C temperature rise. Table 8 lists those Wet Tropics frog species considered most vulnerable to even a moderate temperature rise.

Table 8. Frog species endemic to the Wet Tropics of Queensland considered vulnerable to a 1 °C rise in temperature. For these species a loss of 50% of their core environment is predicted (Adapted from: Williams et al. 2003).

Common name	Scientific name
Tapping nurseryfrog	*Cophixalus aenigma*
Magnificent broodfrog	*Pseudophryne covacevichae*
Rattling nurseryfrog	*Cophixalus hosmeri*
Carbine barred frog	*Mixophyes carbinensis*
Bellenden Ker nurseryfrog	*Cophixalus neglectus*
Dainty nurseryfrog	*Cophixalus exiguus*
Mountain nurseryfrog	*Cophixalus monticola*
Northern tinkerfrog	*Taudactylus rheophilus*

McDonald (1992) noted that regions characterised by high levels of precipitation at higher altitudes (cloud forests) contained the greatest number and diversity of frog species. A rise in the basal altitude of the orographic cloud layer would have serious consequences for many frog species. Microhylid frogs [46], for example, rely on cloud mist for their long-term survival. The disappearance of around 20 frog species in the highland forests of Monteverde, Costa Rica, was probably due to changes in the extent of mountain mist following an increase in temperature (Pounds et al. 1999).

Reptiles of Gondwanan origin including geckoes and skinks.

There are 24 species of Wet Tropics reptiles dependent on rainforest for their survival, of which 18 are endemic to the region. Some relict species, including the bartle frere skink (*Techmarscincus jigurru*), are confined to altitudes over 1,400 m ASL (Covacevich & McDonald 1991). Several species of skinks have been identified as sensitive to a rise in temperature of just 1.0 °C (Williams et al. 2003). The skink species listed in Table 9 are at risk of losing about 50% of their core environment due to a moderate rise in temperature.

Table 9. Skink species endemic to the Wet Tropics of Queensland considered vulnerable to a 1.0 °C rise in temperature. For these species a loss of 50% of their core environment is predicted (Adapted from: Williams et al. 2003).

Common name	Scientific name
Thornton Peak skink	*Calyptotis thorntonensis*
bartle frere skink	*Techmarscincus jigurru*
Czechura's litter skink	*Saproscincus czechurai*
skink (no common name)	*Saproscincus lewisi*
skink (no common name)	*Lampropholis robertsi*
skink (no common name)	*Eulamprus frerei*
skink (no common name)	*Glaphyromorphus mjobergi*

46 Microhylid frogs lay their eggs on the forest litter and therefore require a constant source of moisture from the cloud stripping process to prevent desiccation of eggs and larvae (Williams & Hero 2001).

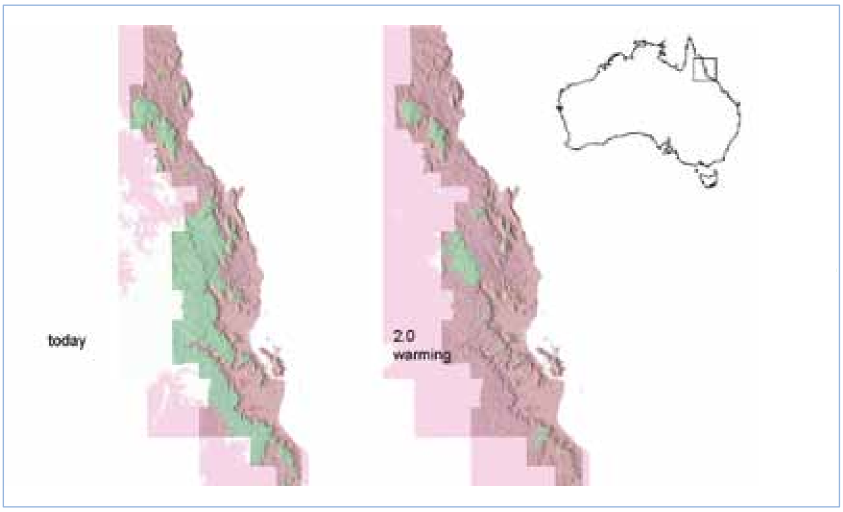
Environmental influences on phenotypic traits (sex, size, shape, etc.) in reptiles are well documented (Shine 1989). The eggs of reptiles depend on the certain narrowly defined nest temperatures for sex determination and survival (TSD), therefore higher temperatures associated with climate change could have a bearing on reptile phenotypic determination.

Mammals, including nine species of dasyurids including one relict species, *Antechinus godmani*, the musky rat-kangaroo (*Hypsiprymnodon moschatus*), the most primitive of the kangaroos and the only living member of its group, and five species of ringtail possums, including four rainforest-dependent species.

Like most of the endemic frog and bird species, the majority of regionally endemic mammals are also located in the higher altitude parts of the Wet Tropics of Queensland (Winter 1991). The determination of thermal tolerance levels for many species has been based indirectly on their current altitudinal range limits. Mammals with a narrow climatic range may find it difficult to shift to a suitable climatic envelope in response to an increase in temperature. For example, some bat species, including the rare tube-nosed insectivorous bat (*Murina florium*), have a very narrow annual mean temperature range (Winter 1991). In situ studies have also shown that the distribution of many arboreal folivores is limited by thermal tolerances; for example, the green ring-tailed possum (*Pseudochirops archeri*) is highly sensitive to ambient temperatures above 30.0 °C, with lethal effects possible within a period of less than five hours (Williams et al. 2003). As most climate change models predict both rising mean temperatures and more frequent periods of extreme temperatures, it is likely that the marsupial folivores will be particularly sensitive to predicted climate changes.

Figure 8 models how climate change may affect the spatial extent and pattern of cool habitats where the average temperature is less than 22.0 ºC. This approximates the temperature threshold for most arboreal leaf-eating mammals (such as possums) in the Wet Tropics (Rainforest CRC 2003).

Figure 8. Areas in the Wet Tropics of Queensland with mean annual temperatures less than 22.0 °C (green) in today's climate (left) and after 2.0 °C warming (Source: modified from Rainforest CRC 2003).



In contrast, species with wider bioclimatic tolerances would have a greater capacity to adapt to an increase in temperature. Species at lower elevations may respond by moving to higher altitudes to take advantage of cooler temperatures.

Modelling work by Williams et al. (2003) showed that several mammal species would lose 50% of their core environment with only a 1.0 °C temperature rise (Table 10). These mammals include the Daintree River ringtail possum (*Pseudochirulus cinereus*), lemuroid ringtail possum (*Hemibelideus lemuroides*), Herbert River ringtail possum (*Pseudochirulus herbertensis*), Atherton antechinus (*Antechinus godmani*), mahogany glider (*Petaurus gracilis*) and the northern subspecies of the spotted-tailed quoll (*Dasyurus maculatus gracilis*).

Table 10. Mammal species endemic to the Wet Tropics of Queensland considered vulnerable to a 1.0 °C rise in temperature. For these species a loss of 50% of their core environment is predicted (Adapted from: Williams et al. 2003).

Common name	Scientific name
Atherton antechinus	*Antechinus godmani*
Mahogany glider	*Petaurus gracilis*
Daintree River ringtail possum	*Pseudochirulus cinereus*
Lemuroid ringtail possum	*Hemibelideus lemuroides*
Herbert River ringtail possum	*Pseudochirulus herbertensis*
Spotted-tail quoll	*Dasyurus maculatus gracilis*

The effects of rising temperatures and periods of extreme temperatures will be compounded by the impacts of increased CO_2 levels—reductions in the nutritional value of leaves, and increased toughness and increases in defence compounds of leaves (Williams et al. 2003). Various studies have shown that elevated atmospheric CO_2 can cause metabolic changes in plants, which results in an increase in the synthesis of leaf tannins and phenolics (Curtis & Wang 1998; Koricheva et al. 1998). High concentrations of these leaf compounds could be detrimental to many herbivores, and could potentially affect the fecundity and abundance of these animals (Hume 1999; Kanowski 2001). Sensitivity to foliage quality has also been observed among endemic marsupials, with some species (e.g. the lemuroid ringtail possum (Hemibelideus lemuroides) exhibiting a greater tolerance level than others (e.g. the Herbert River ringtail possum (Pseudochirulus herbertensis)) (Goudberg 1990).

Rainforest birds, including those of Gondwanan origins such as the southern cassowary, the orange-footed scrubfowl (*Megapodius reinwardt*) and the Australian brush-turkey (*Alectura lathami*).

The distribution and habitat requirements of bird assemblages in the Wet Tropics of Queensland are well documented (Crome & Nix, 1991; Hilbert et al. 2004; Williams et al. 1996). Of the 13 endemic bird species found in the Wet Tropics, nine are confined to altitudes above 600 m ASL. Ten species have specific bioclimatic requirements and are restricted to regions where temperatures do not normally exceed 21.4 °C (Crome & Nix 1991). Some of these cooler-adapted endemics are considered relicts of the Australo-Papuan songbirds.

Williams et al. (2003) identified three endemic bird species in the Wet Tropics of Queensland that are at greatest risk from climate change. These are the golden bowerbird (*Prionodura newtoniana*), Atherton scrubwren (*Sericornis keri*) and the mountain thornbill (*Acanthiza katherina*). These species occur at high altitudes (usually above 600 m ASL) and are considered highly sensitive to a moderate rise in temperature. Bioclimatic modelling indicates that a 1.0 °C temperature rise will result in a 50% loss of core habitat for these bird species.

Table 11 summarises the bioclimatic envelopes of 13 endemic birds of the Wet Tropics of Queensland.

Table 11. Bioclimatic characteristics of bird species endemic to the Wet Tropics of Queensland (Crome & Nix 1991). Species are listed in order of vulnerability.

Species	Altitude (m)			Annual temperature (°C)		
	Mean	Min.	Max.	Mean	Min.	Max.
Golden bowerbird (*Prionodura newtoniana*)	960	680	1260	19.7	18.3	21.4
Atherton scrubwren (*Sericornis keri*)	960	690	1260	19.7	18.3	21.4
Mountain thornbill (*Acanthiza katherina*)	950	640	1260	19.8	18.4	21.6
Bower's shrike-thrush (*Colluricincla boweri*)	950	640	1260	19.7	18.3	21.4
Tooth-billed catbird (*Scenopoeetes dentirostris*)	930	600	1230	19.8	17.6	21.6
Australian fernwren (*Oreoscopus gutturalis*) gutturalis)	960	600	1520	19.7	16.6	21.7
Bridled honeyeater (*Lichenostomus frenatus*)	925	610	1540	19.9	18.3	21.6
Grey-headed robin (*Heteromyias cinereifrons*)	840	430	1260	20.0	18.4	23.6
Lesser sooty owl (*Tyto multipunctata*)	760	40	1180	20.7	18.5	25.4
Chowchilla (*Orthonyx spaldingii*)	720	60	1160	20.9	18.4	25.3
Victoria's riflebird (*Ptiloris victoriae*)	630	10	1200	21.5	18.5	25.4
Pied monarch (*Arses kaupi*)	530	10	1180	22.0	18.5	25.4
Macleay's honeyeater (*Xanthotis macleayana*)	470	60	1180	22.4	18.5	25.7

8.8.4 Associated threats

The Wet Tropics Management Authority's vegetation mapping program identified over 200 patches of forest dieback in the region's upland rainforests. Subsequent studies isolated several species of the fungus-like *Phytophthora* from trees affected by dieback (Gadek et al. 2001). Apart from the threat of disease, vertebrate pests and weeds are also becoming an increasing problem for park managers. Climate change may exacerbate these threats through direct, indirect and interactive impacts.

8.8.5 Gaps in knowledge and future directions

There are numerous issues that need to be addressed with respect to future climate change for the Wet Tropics of Queensland:

- The impacts of climate change on individual vertebrate species have been relatively well studied and documented, and the climatic tolerances of vertebrate endemic species have been predicted. However, the tolerances of plant species—also acknowledged contributors to the World Heritage status of the area—are largely unknown. Similarly, multi-species, community and ecosystem interactive responses to climate change have not been examined.
- Impact prediction based on bioclimatic modelling of distributions makes assumptions that the species will have no adaptive capacity either though evolution of thermal tolerances or ecological plasticity (where an ecological factor may buffer the species from regional exposure to climate change). These factors need to be considered in more detail as proposed by Williams et al. (2008). This requires examination of reproductive characteristics, environmental physiology and quantification of the buffering capacity of topographic and microhabitat refugia.
- The impact of climatic extremes needs closer attention, including heat waves and droughts. These types of extreme short-term events are likely to have even more devastating impacts than increasing averages. Temperature extremes have recently been implicated in the decline of the lemuroid ringtail possum on the Carbine Mountain Range (Williams, pers. comm., unpublished data).
- The lack of weather monitoring stations and programs has made it difficult to determine whether temperature increases and drier conditions are having impacts on the ecosystems of the Wet Tropics (D Hilbert, 2006, pers. comm.). The majority of climate change studies conducted in the Wet Tropics of Queensland have had to focus on the use of models to predict climate change impacts.
- Better water management strategies need to be developed, especially if conditions become drier. The nature and downstream impacts of changes to the orographic cloud layer need to be researched, as the potential impacts on fauna and flora are likely to be significant, though actual impacts are largely unknown.
- Sympathetic management of naturally vegetated land, both on and off-reserve is essential for maintaining the integrity of the biodiversity values of the Wet Tropics of Queensland.
- The purchase of land for future conservation of vulnerable species should be explored further. Recent purchases of land for the future conservation of World Heritage values have focused on the lowlands, but this could be extended to include upland areas.
- There is a need to examine prime habitats for endangered species and, if necessary, to develop a revegetation strategy for regions where land clearing has taken place. This has been suggested as a conservation strategy for the Lumholtz tree-kangaroo (*Dendrolagus lumholtzi*) (Kanowski et al. 2003).
- The impact of weeds, pests and feral animals in association with climate change requires further investigation.

8.9 Shark Bay, Western Australia

Big Lagoon at Francois Peron National Park. *Lochman Transparencies*

8.9.1 Climate change scenarios for Shark Bay, Western Australia

The following climate change projections for south Western Australia, relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[47]

- Average annual temperatures will increase 1.1 °C ± 0.7 °C by 2030.
- A significant decline in rainfall is likely (-11% ± 11%) with a greater chance of winter and spring declines than summer and autumn.
- Evaporation will increase by 4.2% ± 3.1%, exacerbating reduced availability of rainfall and further reducing flows.
- There will be an increase in the frequency and intensity of wind events, along with a 5–10% increase in average wind speed.
- Sea level is expected to rise by about 17 cm by 2030.[48]

8.9.2 Summary of impacts

Shark Bay, Western Australia occupies about 2.2 million ha of marine and terrestrial reserves located midway along the coast of Western Australia between 24°44'S–27°16'S and 112°49'E–114°17'E. The property centres on Shark Bay, an extensive area that features over 30 islands and several outlets to the Indian Ocean. Much of the bay is shallow and is thus hypersaline. It occurs at the northern limit of a transition between temperate and tropical marine fauna, and between temperate and arid

47 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

48 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

terrestrial environments. It overlaps the Eremaean and South West botanical provinces.

Management of Shark Bay involves state and local government agencies, including the Western Australian Department of Environment and Conservation, the Western Australian Department of Fisheries, the Shires of Shark Bay and Carnarvon (Department of Environment and Conservation 2009, pers. comm.) as well as commercial prawn fishers, tourism operators (especially ecotourism) and Indigenous communities (Conservation Commission of Western Australia 2005; Hancock et al. 2000; Lukeman 2005).

The region supports a range of uses. Interactions among the reserves, and with the Francois Peron National Park and adjacent areas, potentially have strong impacts on Shark Bay's World Heritage values, and these are reflected in broad planning for the region.

Increased temperatures may be accompanied by more frequent, and more severe, droughts. At Shark Bay, there is expected to be less abundant and more unpredictable rainfall, affecting conditions on land. This will increase pressure on native fauna and flora from pests such as rabbits and cats, and increase the salinity of Shark Bay and estuaries.

Sea level rise is a threat to values in marine World Heritage properties, but competition for reduced water supplies, as a result of climate change, has received less attention.

Pastoral activities around Shark Bay, such as goat farming and sheep farming, could exacerbate the impacts of climate change (increased temperatures and reduced rainfall) on some of the biological values of Shark Bay, increasing pressure on native vegetation and its dependent fauna.

Marine impacts will depend upon large-scale processes, such as changes to the Leeuwin Current. Influxes of oceanic water have the potential to substantially alter Shark Bay's ecology by diluting hypersaline environments and affecting coastal geomorphology. Salintiy gradients are a major determinant of ecosystem productivity and biodiversity patterning. However, it is likely that the hypersaline environment of the eastern bay will be maintained, except if large changes in sea level occur.

A substantial rise in sea level has the potential to impact on several marine values of Shark Bay, including seagrass and stromatolite features, and would affect the topography of the region (with an impact on outlying islands in particular) through inundation and erosion/deposition associated with storms. However, human use of the bay is likely to have a greater impact on heritage values in the short term, particularly if the pastoral industry is economically buoyant.

Relatively small sea level change could also impact marine World Heritage values of Shark Bay, including mangrove communities and the loggerhead turtle rookery located on the narrow bases of steep cliffs on Dirk Hartog Island.

There is no comprehensive study of the impact of potential climate change on the property. However, there is concern about climate change threats to Shark Bay's ecosystems. These include potential reductions in populations of endangered terrestrial mammals, and the effects of changes in salinity and increased storm frequency on seagrass habitats. There is also concern about the effects of changes in the Leeuwin Current and sea temperature on the relationships between sharks and other marine species (Heithaus 2001; Pattiaratchi & Buchan 1991; Short et al. 2001; Short & Neckles 1999).

Sea grass meadow. *Lochman Transparencies*

8.9.3 *Potential climate change impacts on World Heritage values*

Impact on natural values

Natural criteria

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Criterion (x): To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Values include:

Diverse and abundant examples of stromatolites/microbial mats; Hamelin Pool and the L'haridon Bight environment.

As the simplest lifeforms on the property, the stromatolites in Hamelin Pool and other locations are likely to be less vulnerable to climate change than other species such as the endangered mammals (Papineau et al. 2005). Increases in atmospheric CO_2 concentrations, water temperature and salinity (due to increased evaporation; reduced streamflow in the Gascoyne and Woramel rivers; and lower, more episodic rainfall) do not appear to pose a substantial threat to these World Heritage values. Sea level rise is likely to have a more significant effect on other components of Shark Bay's ecosystems.

Steep salinity gradients due to development of banks and sills in Shark Bay; three zones caused by differing salinity levels; oceanic development of a landlocked marine basin forming a reversed estuary containing hypersaline waters; vast, rare and scientifically important deposits of organic shells (*Fragum erugatum*); coquina, ooid shoals, lithified sediments, broad supra-tidal flats with evolution of subsurface evaporitic deposits and meromictic blue ponds; modification of the physical environment (e.g. build-up of banks and sills, and water currents, caused by extensive seagrass beds).

A substantial rise in sea level would affect the topography of the region and affect the habitats on the outlying islands through inundation, erosion and deposition associated with storms. The steep salinity gradients may be reinforced by the effect of climate change on the Leeuwin Current (Pattiaratchi & Buchan 1991; Woo et al. 2006).

There is no clear evidence that other aspects of climate change—such as increases in atmospheric CO_2 concentrations, temperature, or more frequent and severe winds—will significantly affect the morphology of the property. While there has been no extensive research on the likely impacts of these factors in relation to the values listed above, the existing research literature suggests that there will not be significant changes to the geography of Shark Bay, such as formation of new shoals, erosion of lithified sediments and shell deposits (Pattiaratchi & Buchan 1991; Woo et al. 2006).

Restricted communities of marine organisms that have developed physiological adaptations to tolerate hypersaline conditions including the bivalve Fragum erugatum, zooplankton; seagrass-based ecosystems including nutrient cycling, food chain, nursery grounds, variety of habitats and creation of steady-state hydrological conditions.

Shark Bay is an extensive area that features over 30 islands and has several outlets to the Indian Ocean. Much of the bay is shallow and hypersaline. It features a rich array of flora and fauna, including major seagrass beds, dugong, the migratory Humpback whale, snapper, stromatolites, sharks, turtles, and over 230 species of birds, reptiles and several mammals, including the burrowing bettong (*Bettongia lesueur*) (Richards 2003). The isolation of habitats on islands, such as Dorre Island, and peninsulas, has protected some of the mammal and reptile species from the disturbance evident elsewhere in Western Australia. This is reflected in Project Eden[49], which has been successful in reintroducing endangered species to those locations, and in reducing predator populations (Algar & Burrows 2004; Morris et al. 2004; Parsons et al. 2002).

The Shark Bay property is large and it contains a diversity of marine habitats. However, an assessment of the likely effects of climate change on the property is restricted by scant research. It is not clear whether climate change will fundamentally affect the steady-state conditions evident in parts of Shark Bay and erode its World Heritage values. The consequences of increased sea level, changing water chemistry and increased temperature for these specialised ecosystems are unknown. Further research to identify the specific impacts of climate change and its effects on Shark Bay's heritage values is required.

One of the most extensive seagrass meadows in the world; highly species-rich assemblage of seagrasses; physical structure of Wooramel Seagrass Bank.

The seagrass meadows are significant both in their own right and as part of an ecosystem that features snapper, dugongs, turtles and sharks (Aragones & Marsh 2000; Nahas et al. 2003; Preen 1998). Research of climate change impacts on seagrass has identified a range of concerns, including elevated sea levels (greater water depths), changed tidal variation and current flow, seawater intrusion into estuaries and rivers, salinity change, and increases in the intensity and frequency of storms (Short & Neckles 1999). Their effects may include changes in reproductive patterns, relocation of some species, decreases in the number of plants within a bed and reduction in the mass of individual plants (Short et al. 2001).

There is, however, some uncertainty about these effects and further research is needed to address particular questions. As the annual rainfall in Shark Bay is low (<250 mm), and very little permanent surface freshwater exists in the area, it is unlikely that climate change will significantly affect either currents in Shark Bay or increase the runoff from the Gascoyne

49 For more details on Project Eden, see <http://www.sharkbay.org/terrestrial_environment/page_08.html>.

River, thereby increasing turbidity and decreasing growth in seagrass meadows through reduced light. The impact of raised temperatures and increased atmospheric CO_2 concentrations is uncertain; Short et al. (2001) suggested that higher levels may promote seagrass growth, but it is unclear whether long-term CO_2 enrichment would result in sustained increases. Competition between seagrass and algal species is an area for further research. Short et al. (2001) also speculated that increases in UV-B radiation due to climate change may have varying effects, including inhibition of photosynthetic activity.

Isolation of faunal habitats on islands and peninsulas, and evolutionary processes illustrated in fauna such as the rufous hare wallaby and banded hare wallaby; isolated populations of Australian mammals demonstrating evolutionary processes; transition zone between major marine ecological provinces including the northern limit of a transition region between temperate and tropical marine fauna, with resulting high species diversity.

Climate change appears unlikely to affect the isolation of Shark Bay's islands and undermine initiatives such as Project Eden (Baynes 1990; Hancock et al. 2000; Morris et al. 2000).

Movement of zonal boundaries, with the temperate zone retreating south and Shark Bay increasingly favouring arid zone flora and fauna, is potentially the major impact of climate change in this World Heritage property. Increased sea temperature may favour a southwards movement of tropical marine species. However, the effect that climate change will have on currents along the continental shelf, on fish stocks and on the Leeuwin Current in particular, is uncertain (Nahas et al. 2003; Pattiaratchi & Buchan 1991; Watson-Capps & Mann 2005; Woo et al. 2006). Increased sea temperatures would appear likely to increase the frequency and effectiveness of predation of turtles (*Chelonia mydas*, *Caretta caretta*) and dugong (*Dugong dugong*) by the tiger shark (*Galeocerda cuvier*) (Bejder & Samuels 2003; Heithaus 2001; Heithaus et al. 2002).

Transition zone between the South West Botanical Province dominated by *Eucalyptus* species and the Eremean Province dominated by *Acacia* species, vegetation of the southern Nanga and Tamala areas, the northern 'end of range' for numerous southern faunal species, coastal 'end of range' for arid interior species, including numerous known species of herpetofauna, and a notable diversity of plant and animal species (which includes an estimated 35% of Australia's total bird species).

This World Heritage value is likely to be affected by climate change, through movement of zonal boundaries reflecting changed abundances of species in different areas associated with relocation, expansion or loss of species, and possibly changed total diversity. The nature of changes that may happen—and the extent to which trends in populations can be addressed through management measures such as pest control, introduction/reintroduction/relocation of threatened species and fire management—is not well understood.

Stromatolites, seagrass meadows at Wooramel Bank, the diversity of landscapes formed by aridity, peninsulas, islands and bays; exceptional coastal scenery at Zuytdorp Cliffs, Dirk Hartog Island, Peron Peninsula, Heirisson and Bellefin Prongs; strongly contrasting colours of dunes and cliffs of Peron Peninsula; extensive annual wildflower displays associated with the richness of flora.

The geomorphology of the region means that impacts on aesthetic values are dependent on the extent and nature of the impact of climate change. There is insufficient research for a definitive assessment. There may be little tangible effect on the landscape, and the topography and colour of dunes and cliffs may remain intact. Wildflower displays are, however, likely to be affected by changes to species resulting from increased temperatures, reduced rainfall and more severe droughts. These factors will result in increased morbidity of some species, population stress resulting from reduced germination and greater pressure from herbivores. The ongoing viability of these isolated populations is likely to be threatened if periods of low rainfall projected under climate change eventuate (Western Australian Department of Environment and Conservation, pers. comm.).

The most important and significant habitats where threatened species of plants and animals of outstanding universal value from the point of view of science and conservation still survive, including plant species of conservation value, terrestrial animals (including *Bettongia lesueur, Lagorchestes hirsutus* and *Perameles bougainville*); marine animals (including *Dugong dugong, Megaptera novaeangliae* and *Chelonia mydas*), reptiles and birds (including *Amytornis textilis).*

Climate change is likely to increase pressure on particular species on the islands and in the mainland reserves. Rising temperature, increased storm severity and frequency, and increased atmospheric CO_2 levels will affect particular habitats, especially those occupied by reptiles and terrestrial mammals. Effects could include population declines resulting from increased predation, increased competition from rabbits, and reduced fecundity due to higher temperatures and water stress (Parsons et al. 2002; Short et al. 1997; Richards 2003).

The results of recent surveys of mammal populations on Bernier and Dorre Islands suggest that climate change may affect the security of the threatened mammal populations on these islands. Data from historical records and recent surveys indicate large natural fluctuations of populations (large mortality rates and population declines in drought, which are usually followed by increased reproduction and survival when rainfall conditions improve). More frequent and severe droughts could potentially put populations below threshold levels, such that they could decline to extinction before seasonal conditions improve sufficiently for them to recover as they have done in the past (Department of Environment and Conservation, pers. comm.).

Much of the Shark Bay flora has adapted to the prevailing saline conditions. However, recovery after fire is affected by factors such as temperature, the availability of water, predation by species such as rabbits, and competition from other plant species. Climate change is likely to increase the severity of drought in the area as well as the frequency of lightning-initiated fires. That is of potential concern on the smaller islands and mainland refuges that provide habitats for populations of endangered terrestrial animals.

8.9.4 Gaps in knowledge and future directions

The following climate-related issues need to be addressed.

There is an incomplete understanding of the property's ecosystems and of the potential impacts of climate change. The consequences of increased sea level, changing water chemistry and increased temperature for these specialised ecosystems are unknown. In addition, there is a need to investigate the condition of the wider Gascoyne and Wooramel River catchments, and their impact on the World Heritage values of Shark Bay.

Not all the species present have been identified and there is a limited understanding of species interrelationships. A complete inventory and an assessment of particular vulnerabilities are required. Systematic monitoring of the impacts of fire, and study of the risk of incursion of feral animals—associated with climate change and other factors such as development outside the property boundaries—is also necessary.

There is a need to better understand the implications of climate change for human uses of the area. There is commercial use of Shark Bay and its environs for minerals extraction and prawn fishing. Ecotourism depends on a wide range of natural values, including the presence of migratory whales, turtles, dolphins and dugong. Pressure from ecotourism activities is likely to increase, as the public's perception of the threats of climate change for continuing access to these opportunities increases (Bejder & Samuels 2003; Beyer et al. 2004; Buckley 2004). A detailed evaluation of impacts at the species, ecosystem and process level is required, involving all stakeholders (Lukeman 2005).

8.10 Fraser Island

Eastern beach, Fraser Island. *Shannon Muir and the Department of the Environment, Water, Heritage and the Arts*

8.10.1 Climate change scenarios for south-east Queensland

The following climate change scenarios for south-east Queensland, relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[50]

- The average annual temperature is expected to rise by 1.3 °C ± 0.6 °C by 2030, with an increase in the number of hot days.
- Average annual rainfall is expected to decrease by 3.5% ± 11%, with a higher evaporative demand, leading to reduced runoff and a decrease in groundwater recharge, which may reduce the supply of water to spring-fed streams and lake systems.
- Extreme weather events are likely to become more frequent.
- There is likely to be an increase in the frequency and severity of droughts, as well as an increased risk of severe fire events (Hennessy et al. 2006).
- Extreme weather events are more likely, leading to increased flash flooding.
- Sea level is expected to increase by about 17 cm by 2030.[51]

50 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

51 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

8.10.2 Summary

Fraser Island, situated off the south-east coast of Queensland (24°35'–26°20'S, 152°45'–153°30'E), is the world's largest sand island, covering an area of 184,000 ha.

An increase in extreme weather events may result in an acceleration of natural dune erosion and formation processes. The occurrence of more frequent and intense fires, and prolonged drought, may also lead to changes in the composition and distribution of the island's vegetation. The island is a popular tourist destination, especially for four-wheel drive enthusiasts, and increased visitor numbers may place additional stress on its natural values and resources, especially water resources. Water extraction by the local community is an important factor affecting the integrity of the island's World Heritage values. Sea level rise and storm-surge events are likely to result in saline intrusion into freshwater systems.

8.10.3 Potential climate change impacts of World Heritage values

Impact on natural values

Natural criteria

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Values include:

Evolving coastal dune formations, chronosequence of podsol (soil that developes in temperate to cold moist climates) development.

The island's parabolic dune system is unique in terms of age, diversity and number of dunes. The dunes show a long history of formation and associated climate change processes, extending back in time to the late Quaternary epoch (Ward 1977). However, the precise dates of old dune formation are largely unknown, and estimates of future dune formation rates due to climate change and anthropogenic effects are uncertain. The island's dune systems are considered generally 'robust', provided the vegetation cover remains relatively undisturbed (EPA 2004).

Water-eroded Pleistocene dunes, occupying about a third of the island (EPA 2004), represent ongoing pluvial and fluvial processes (Thompson 1983, 1992). Vegetative cover protects the dunes from erosion and dissipation by wind and water. Dune systems erode over long time periods (EPA 2004), but the rate of erosion is largely determined by the amount of vegetation cover (Bridge & Ross 1983). Fire, by reducing vegetation cover, can lead to an increase in the rates of dune erosion (Bridge et al. 1985) and fire management is an essential tool to ensure the long-term preservation of the dune system.

Studies of plant succession conducted at Cooloola [52] (situated about 10 km south of Fraser Island) show that younger dune systems support progressive stages of vegetation succession. They are also more resilient to human disturbance than the older dune systems, which display retrogressive stages of plant succession (Walker & Thompson 2004). However, the sand-surface properties of the younger dunes repel water droplets far more effectively than the older dune systems (Bridge et al. 1985). This repulsion effect also prevents water from seeping into the substrate, leading to direct runoff and erosion on dune slopes.

52 Cooloola, situated less than 10 km south of Fraser Island, is not listed as World Heritage but has landscape characteristics similar to those on Fraser Island.

Sand blow, Fraser Island. *Paul Candlin*

There has been no specific research on future climate change impacts on dune formation and erosion on the island, and it is difficult to predict the potential impacts of future climate change on the natural processes of dune formation and reduction. Empirical data and simulation show that surface erodibility (a function of vegetation cover and available moisture) and wind-induced erosion (a function of wind energy) play an important role in dune dynamics. These two processes are likely to be altered by climate change (Thomas et al. 2005). The likelihood of increased dune erosion due to increased cyclones has also been documented (Nott 2006). Higher storm surges associated with increased storms and sea level rise are also likely to increase dune erosion. It is therefore likely that increased action of both wind and water resulting from climate change, combined with the changes to vegetation cover exacerbated by an altered fire regime, will lead to an acceleration in dune dynamics.

Freshwater dune-lake systems.

Spring-fed lakes and streams on the island are considered to be quite stable (EPA 2004). However, tourist activities have resulted in a considerable loss of riparian vegetation around the lake systems, increasing the risk of erosion. The effects of erosion and human activity on geochemical and geomorphological processes are evident at several locations, including at Lake Wabby, where human activity has accelerated the natural process of lake infilling (EPA 2004).

Little is known about the potential impacts of climate change on the three types of lake systems (perched, window and barrage lakes) on the island. The three lake systems are quite different from one another. They can be colourless, or have a dark brown appearance, indicating that the in-lake processes differ. Water temperature affects the chemical, physical and biological processes in lakes, changing their acidity, solubility, nutrient dynamics and phytoplankton production (McKnight et al. 1996; Smol & Cumming 2000). The lakes on Fraser Island derive their water primarily from aquifers. Prolonged drought and/or water extraction may affect the supply of water to spring-fed streams and lakes. Eutrophication caused by recreational activity is already a major concern, and is likely to be exacerbated by higher water temperatures.

Patterned swampy fens and sheltered mangrove areas.

Fraser Island has a unique wetland system containing peat vegetation, commonly known as 'mires'. The occurrence of mires at sub-tropical latitudes is rare and they are normally found in cold climates where lower temperatures and slower decomposition rates assist in peat formation. Mires, which obtain their water and nutrient supply from groundwater (as opposed to bogs, which obtain their water from rainfall), are referred to as fens.

A combination of drought, fire and water extraction poses a serious threat to the patterned fens of Fraser Island. During periods of drought, fens often become dry and burn for weeks following extreme fire events (EPA 2004). More intense and more frequent fire events could be detrimental to fen systems.

Mangrove communities are also at risk from these combined threats including changes in water salinity (Bunt et al. 1982; Duke et al. 1998). In humid regions, mangrove swamps are continuously flushed with freshwater from surface flow and/or by groundwater discharge. Species diversity in mangrove forests is significantly influenced by rainfall and frequency of freshwater runoff from riverine catchments into intertidal zones (Ball 1998; Duke et al. 1998; Ewel et al. 1998). Reduced inflows to the groundwater could lead to a reduction of freshwater flows into intertidal areas, and may alter the spatial distribution of mangrove communities through higher salt concentrations.

Large diversity of plant and animal species.

The vegetation communities of Fraser Island are highly diverse, ranging from rainforests to open, shrubby woodlands. The nutrient cycle on Fraser Island is a unique feature of the island's hydrological cycle (Walker et al. 1981; Walker & Thompson 2004). Plants obtain nutrients either directly from the underlying sand dunes, or from the atmosphere via nitrogen fixation or from sea spray (Thompson 2004). An increase in fire intensity and frequency could affect nutrient availability for many plant species on the island. Vegetation in the retrogressive stages is less likely to recover from nutrient loss due to fire, but the progressive stages of vegetation succession can generally recover from short-term nutrient loss by drawing on nutrients locked in the underlying sands (Walker & Thompson 2004). Thus, the fire regime can affect vegetation regeneration and successional sequences on dune systems. It can also have an influence on the position of the boundary between rainforest and sclerophyll forest (Sandercoe 1986, cited in Walker & Thompson 2004). A changed fire regime could therefore result in the replacement of wet forests with dry woody species (EPA 2004).

A change in the fire regime would also pose a major threat to the island's fauna through the destruction of vital habitats. Fraser Island provides a valuable refuge for threatened and rare species that are also present on the mainland. Patterned fens support a range of aquatic fauna including rare and vulnerable frog species, such as *Crinia tinnula*, *Litoria freycineti*, *L. olongburensis* and *L. cooloolensis*.

The fens also provide an important habitat to vulnerable birds, such as the ground parrot (*Pezoporus wallicus*), fish (*Nanoperca oxleyana*, *Pseudomugil mellis*) and mammals (e.g. the false water-rat, *Xeromys myoides*).

The optimum fire regime, which would ensure sustainable peat development and the fauna it supports, has not been determined (EPA 2004). Apart from the effects of fire, lowering of the watertable, by long-term drought or water extraction, would inevitably impact on the hydrology and nutrient cycling occurring in patterned fens.

Water extraction on the island currently poses a major threat to the integrity of its World Heritage values, and its effect could be exacerbated by a climatic shift towards drier conditions. Although large shifts in the hydrological regime are not historically uncommon, water extraction could accelerate the changes in vegetation patterns with climate change.

Core samples taken from the Old Lake Coomboo Depression, which is situated on top of one of the oldest dune systems on the island, demonstrate that the island has experienced significant hydrological change spanning numerous glacial periods (Longmore 1997). These hydrological changes have also been accompanied by changes in vegetation patterns as a result of decreases in rainfall over the past 350,000 years (Longmore 1997).

The sedimentation record for this region of the island shows that there was a distinct shift in vegetation type from predominantly rainforest to sclerophyll forest associated with changes in precipitation and hydrological regimes (Longmore & Heijis 1999). Long-term changes in climate have major implications for the survival of relict rainforests (Longmore 1997) and continuing long-term decline in rainfall will ultimately have an impact on plant diversity as well as nutrient cycling.

A climate-induced change in water quality is also a factor that could affect the aquatic environment. Many aquatic species may respond directly to changes in climatic variables, such as temperature, but are more likely to be affected by climate-induced changes to limnological variables such as pH, stratification, water depth and nutrient loading (Smol & Cumming 2000). High salinity levels in intertidal zones can also be lethal to a variety of aquatic organisms including microbes, vertebrates and invertebrates (Muschal 2006).

8.10.4 Associated threats

There is an increasing risk to the natural heritage values of the island from increased visitation and overcrowding; the impacts of climate change on these trends are unknown. Invasive species such as the Pandanus leaf-sucking insect (*Jamella australiae*), feral cats, mosquito fish (*Gambusia holbrooki*) and the cane toad (*Bufo marinus*) are regarded as major threats to the island's natural values (EPA 2004). Several introduced plant species including bitou bush (*Chrysanthemoides monilifera*) and lantana (*Lantana camara*) are a problem on Holocene dunes. The impact of climate change on these invasive species, and the impacts of the invasive species on the natural values of the island in the presence of climate change, is unknown.

8.10.5 Gaps in knowledge and future directions

- A greater understanding and knowledge of dune formation, especially the dates of dune system formation, would provide managers with the ability to predict changes in dune morphology, providing a sound basis for their future management.
- There is little knowledge or understanding of the functional processes affecting the dune life cycle, or of its impact on flora and fauna. There is also very little knowledge of human-induced changes in the landscape. The lack of knowledge of these issues makes it difficult to assess future climate change impacts.
- Accurate soil maps are needed for Fraser Island. They will help identify the areas at greatest risk from climate change and greatly assist in the development of management strategies to protect them from climate change impacts and anthropogenic agents.
- There is little palynological information available from the island's lakes. Palynology has a diverse range of applications. It can be used to determine former climatic conditions, providing insight to former terrestrial and marine environments, and assisting with management planning.
- A better understanding is required of the effects of drier conditions on the island's hydrological processes, and of increased water extraction on hydrological processes. The impact of water extraction has not been fully recognised or adequately addressed. However, although increased water extraction from Fraser Island is potentially a high-risk activity, the actual likelihood of the threat being realised is rated as low (EPA 2004).
- The biology of many lake and wetland vertebrate and invertebrate species is poorly understood. The potential possible increased threats from exotic species (e.g. *Gambusia* and cane toads) under climate change are unknown and need further research.
- There is a need to identify the optimum fire regime for the island's habitats, and the fauna and flora they support. It is an essential management issue. Some species (e.g. *Eucalyptus pilularis*) are likely to become extinct without an appropriate fire management regime (EPA 2004). Land managers need to be made more aware of the importance of fire management strategies, such as prescribed burning, to reduce the destructive effects of wildfires.
- Further archaeological research is needed to develop a greater understanding of the relationship between Aboriginal people and Fraser Island's landscape. An understanding of the island's fire history is necessary for the development of an appropriate fire management strategy for the island (EPA 2004).

8.11 Australian Fossil Mammal Sites (Riversleigh/Naracoorte)

Rock outcrops typical of the Riversleigh area. *Colin Totterdell and the Department of the Environment, Water, Heritage and the Arts*

8.11.1 Climate change scenarios for Australian Fossil Mammal Sites

Climate change scenarios for these two properties are likely to vary due to their significant latitudinal differences. The following climate scenarios for both sites are based on a 'high' greenhouse gas emissions scenario.[53]

- Climate change is likely to result in greater frequency and severity of weather events, and a decrease in rainfall at both locations. However, Naracoorte may experience lower annual average rainfall than Riversleigh, with significantly lower rainfall in winter and spring, and least decline in summer rainfall (Table 12).
- Droughts will probably become more frequent and severe at both sites, and evaporation will increase at both sites (3.7%).

Table 12. Temperature and rainfall change based on a high greenhouse gas emissions scenario

	Temperature (average annual ± uncertainty)	Rainfall (average annual ± uncertainty)
Naracoorte	+0.9 °C ± 0.6 °C	-7.5% ± 3%
Riversleigh	+1.3 °C ± 0.6 °C	-3.5% ± 5%

53 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

8.11.2 Summary of impacts

The two Australian Fossil Mammal Sites, at Riversleigh (18°59'S, 138°34'E) in Queensland and at Naracoorte (37°01'S, 140°48'E) in South Australia, are outstanding for the extreme diversity and quality of their fossils. Those fossils represent important and significant steps in the development of Australia's mammal fauna, and provide links between past and contemporary biota in Kakadu National Park, Gondwana Rainforests of Australia and the Wet Tropics of Queensland. Together, the two sites occupy about 10,300 ha. They are administered by the Queensland and South Australian governments.

The sites were nominated as World Heritage properties on the basis of their importance as fossil sites (DEH 2001; Luly & Valentine 1997). The World Heritage values of the sites relate exclusively to their fossil deposits. These values are expected to be largely unaffected by climate change, despite Riversleigh being an open-air site and Naracoorte a cave site.

8.11.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criteria

Criterion (viii): To be outstanding examples representing major stages of the earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Values include:

Outstanding examples of major stages of earth's history, including the record of life, particularly the middle to late Tertiary evolution of the mammals in Australia (Riversleigh), and an outstanding record of terrestrial vertebrate life spanning the last 170,000 years (Naracoorte). Fossil deposits which contain an exceptional abundance and diversity of species and individual specimens; and have a high quality of preservation which enables both reconstruction and detailed anatomical descriptions and functional morphology of both crania and post-cranial skeletal elements.

There is a striking absence of substantive scientific literature dealing with the likely effects of climate change on fossil deposits per se. The literature instead concentrates on site management issues and national regulatory regimes. Discussion of threats in the wider palaeontological literature typically centres on the palaeontological equivalent of 'rescue archaeology'; for example, the discovery of a fossil deposit during civil engineering works such as a highway or dam and threats such as seismic disturbance through blasting in an adjacent quarry or movement of debris from that quarry. However, it is interesting to note that there is extensive discussion of the fossil record in terms of insights about past environmental conditions and climate changes (Gillieson et al. 1996; Reed & Gillieson 2003).

Relict features are, by definition, no longer forming. Damage to them is irreversible, and their destruction results in permanent loss. Their protection thus requires control of activities such as excavation (Sharples 2002) and weathering from severe storm events.

In contrast to active process systems, the protection of relict features can often be achieved with a largely site-based approach that mostly considers the protection of the specific feature itself with less need to consider the ongoing processes in surrounding areas. This is the approach usually taken to protect important fossil sites. Provided the site is protected from excessive artificial excavation or covering, and from accelerated erosion or mass movement, the geoheritage values of the site will be preserved even though ongoing land-forming processes in the surrounding area may be altered by human activities or climate change.

Fossil nautiloid found at Naracoorte. *Australian Heritage Council*

The dominant threat to the values is excessive human visitation and illegal excavation. These threats are addressed in the management plans for both sites and are independent of climate change effects.

The karst landscape at Naracoorte may be at risk from increased erosion through flash flooding and acid rain associated with climate change (Swart 1994). This could possibly affect fossil deposits.

Climate change poses a broader threat to ecosystems at both properties, with potential impacts on bat, insect and other life forms in the Naracoorte caves, but those systems are not recognised as World Heritage values. Research into the effects of increased temperatures, higher CO_2 levels, variations in humidity, and potential reduction of insect populations through fire and vegetation changes is desirable if considering impacts on the cave system beyond protection of the World Heritage values.

8.11.4 Gaps in knowledge and future directions

From a broad climate change perspective, the following issues may be significant for Riversleigh and Naracoorte World Heritage properties:

- The effects of climate change as a risk factor for fossil sites have not been discussed extensively in authoritative, peer-reviewed literature. A more detailed examination is desirable and should include the nature of vulnerabilities, the intensity of threats and potential responses. It should recognise that vulnerabilities differ between the sites.

8.12 Heard and McDonald Islands

Brown Glacier, Heard Island showing meltwater run-off. *Shavawn Donoghue*

8.12.1 Climate change scenarios for Heard and McDonald Islands

- Heard Island's average annual air temperature increased by about 1 °C between 1947 and 2001 (Thost & Allison 2006) and is expected to continue to rise.
- Sea surface temperature is expected to increase by 1–2 °C by 2070 (Hobday et al. 2006), having increased already by 0.75 °C since 1947 (Chambers et al. 2005).
- Sea level is expected to rise by about 17 cm under a 'high' greenhouse gas emissions scenario.[54]
- No data or estimates exist for impacts on rainfall or evaporation.

8.12.2 Summary of impacts

Heard Island (53°06'S, 73°30'E) and the McDonald Islands (53°03'S, 72°36'E) lie in the southern Indian Ocean, on the Kerguelen Plateau, 4,100 km south-west of the Australian continent and 1,500 km north of Antarctica. The islands are 40 km apart, the McDonald Islands to the west of Heard Island. Heard Island is a spectacular ice-covered volcano covering approximately 36,800 ha and rising 2,745 m above sea level, while the highest point in the barren and rocky 1,800 ha McDonald Islands is 230 m. The World Heritage property also includes adjacent offshore rocks and shoals, and all territorial waters to a distance of 12 nautical miles.

The visual effects of climate change are more apparent on the subantarctic islands than anywhere else in Australia. Heard Island showed an average annual air temperature increase of about 1 °C between 1947 and 2001 (Thost & Allison 2006), with higher increases in winter temperatures than summer (Thost & Truffler 2007). Increased warming has led to rapid and accelerating glacial retreat (Thost & Truffler 2007)—exposing large areas of bare ground previously covered by ice—and a reducing area of annual snow cover since 1948 (Bergstrom 2003). Marked glacial retreat has been associated with changed weather patterns (Allison & Keage 1986; Thost & Allison 2006).

54 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

Glacial contraction has also resulted in the formation of freshwater lakes and lagoons. These landscape changes have enabled fauna and flora to colonise newly-exposed areas, changing the distribution and abundance of plant and animal species. It is difficult to predict how global warming will impact on future species distribution, abundance and interspecies competition.

There are no climatic observations for the small and rocky McDonald Islands, which are barren and ice-free.

8.12.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criteria

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Values include:

> Fast-flowing glaciers that retreat and advance quickly in response to changes in temperature and precipitation; evidence of dramatic fluctuation in glacier extent in recent decades, and consequent changes in the total glaciated area; formation of newly deglaciated areas.

Heard Island provides a unique opportunity to study the impact of climate change by observing the rate of glacial retreat and expansion. Changes in glacial activity have been observed and recorded in drawings and photographs since the beginning of the 20th century. Georeferenced satellite imagery has led to improvement in the accuracy of glacial retreat measurements (Ruddell 2006). Heard Island glaciers are estimated to have lost more than 10% of their volume since 1947 (Ruddell 2006). This varies with altitude. Brown Glacier, a small glacier situated on the north-east coast, retreated by 60 m between 2001 and 2004. Its thickness reduced by an average of 10 m at lower elevations and an average of 6 m on the upper slopes (Thost & Truffer 2007). This is equivalent to about a 35% reduction in the volume of the glacier (Truffer et al. 2001). However, many of Heard Island's higher glaciers, above 1,500 m above sea level, have exhibited less than 2% recession (Ruddell 2006).

Between 1947 and 1988 the total area occupied by glaciers on Heard Island decreased by 11%, consistent with a climate-related change rather than being due to the effects of volcanic activity (Ruddell 2006). If precipitation has remained constant, then the recession is equivalent to a 0.8 °C warming since the 1940s (Ruddell 2006). The recession and intermittent advance of the glaciers correlates strongly with increases and decreases in regional sea surface temperature and air temperature (Ruddell 2006; Thost & Allison 2006). Similar glacial changes are expected to result from future changes in regional temperatures. Evaluation of the impact of climate warming on glacial activity requires further monitoring and measurement.

> Areas of newly deglaciated land providing habitat for plants and animals and an outstanding location for researching plant colonisation.

Heard Island provides a unique opportunity to study the response of plants and animals to glacial retreat. Increased exposure of the island's surface terrain as ice margins have receded has led to significant changes in the distribution and abundance of vegetation communities, such as the colonisation of deglaciated areas by the slow-growing cushion plant (*Azorella selago*) (Scott & Bergstrom 2006). However, colonisation patterns are also greatly affected by a range of other factors, such as moisture availability and animal disturbance (Scott 1990).

Extensive glacial retreat has benefited some bird species, such as burrowing petrels, by exposing large areas of bare ground for nesting sites; the presence of birds may enhance plant growth. The impact of continued warming on species distribution and abundance is difficult to predict.

In some parts of the island, there has been a spectacular and ongoing increase in populations of king penguin (*Aptenodytes patagonicus*) (Woehler 2006), dramatically affecting the vegetation by excessive trampling.

Five species of true seals (Phocidae) and two species of eared seals (Otariidae) occur on the islands. Of these, numbers of Antarctic fur seals are rising significantly (Green 2006) and are expected to have a large impact on coastal vegetation structure in the near future (Scott & Bergstrom 2006). Conversely, a decline in pupping rates of land-breeding seals on Heard Island has been observed, coinciding with an increase in sea surface temperatures north of the islands over the past 15 years (Australian National Committee on Antarctic Research 2006). After recovering well from early population declines associated with exploitation, southern elephant seal (*Mirounga leonina*) populations declined by about half between the 1950s and the 1980s (thought to be associated with wide-scale changes in the Southern Ocean beginning in the mid-1960s). However, numbers are currently stable (Australian National Committee on Antarctic Research 2006). McMahon and Burton (2005) concluded on the basis of maternal energetic studies that southern elephant seal populations are likely to be negatively affected by the predicted warming sea surface temperatures.

Seal and seabird populations contribute significantly to the nutrient cycle on sub-Antarctic islands, and excretion by vertebrates enhances plant vitality by increasing nitrogen and phosphate levels in plant tissues (Smith 1977). Although changes in seabird and seal populations appear to be altering the composition and abundance of coastal vegetation, it is difficult to predict the extent of change due to likely additional population increases (K Kiefer 2006, pers. comm.).

The increase in available habitat for plant colonisation, together with joining of previously separated ice-free areas, has led to considerable changes in the vegetation of Heard Island in the past 20 years or so. Changes in the succession and colonisation of plant species have been observed. In regions such as Spit Bay, where vegetation communities are well established, *Acaena* has out-competed the slower-growing *Azorella selago* (Kiefer 2002). It is now expanding in area at the expense of other species, such as *Poa cookii* (Scott & Bergstrom 2006). Heard Island's only recorded invasive plant species, *Poa annua*, also expanded its range between 1987 and 2000, probably aided by increased soil disturbance by seals (Scott & Kirkpatrick 2005). These successional processes are likely to be influenced by rising temperatures (K Kiefer 2006, pers. comm.; Scott & Bergstrom 2006). Further changes in vegetation cover are expected with rising temperatures and continued glacial retreat (Scott & Bergstrom 2006).

> Large breeding populations of flying birds and penguins, and bird predator populations, unaffected by the presence of introduced predators.

The seabirds on Heard and McDonald Islands have not received the same attention as avifauna on other sub-Antarctic islands, such as Macquarie Island. No seabird data have been available for the McDonald Islands since 1980 (Australian National Committee on Antarctic Research 2006). Both population increases and decreases have been observed in a variety of larger Heard Island birds, but the relationship with climate change is not known.

Seven species of penguin are known to breed regularly in, or occasionally visit, the ice-free areas of Heard Island and McDonald Island, and to feed in the oceans surrounding these areas. Penguins on Heard Island have exhibited varying degrees of population change since the late 1940s, with some species, such as the king penguin (*Aptenodytes patagonicus*) displaying a substantial increase in population numbers (Woehler 2006), recovering from near-extinction during the sealing years. Since the early 20th century they have made a remarkable recovery (Gales & Pemberton 1988), doubling in population every five years (Woehler 2006). It is not known if king penguin populations have reached or exceeded their original size.

Current high numbers are thought to be due to enhanced availability of their principal prey (Woehler et al. 2001), possibly due to changed atmospheric and oceanic circulation (Budd 2000).

However, more recent Southern Ocean studies predict king penguins to be at considerable risk from climate change. They feed on small fish and squid, which are diminishing in abundance as a result of warming of the Southern Ocean. This poses a risk to the survival of king penguins, because they have to travel greater distances to find food (Le Bohec et al. 2008), with a 9% decline in the adult penguin population predicted for every 0.26 °C of sea surface warming.

Other penguin species, including macaroni and gentoo (*Pygoscelis papua*) penguins are in decline (Australian National Committee on Antarctic Research 2006; Birdlife International 2000; Woehler 2006). Both species are currently listed as vulnerable under IUCN criteria (Birdlife International 2000). Estimates of seabird populations on Heard and McDonald Islands, their population trends, and IUCN status are summarised in Table 13.

Table 13. Current estimates of selected seabird populations on Heard and McDonald Islands, their population trends, and IUCN status (Birdlife International 2000; IUCN 2007). Errors of estimates are unknown. (Source: Woehler 2006: 129)

Species	Minimum breeding population (pairs)	Population trend	IUCN status
King penguin	40,000 [55]	Increasing	
Gentoo penguin	16,000	Decreasing	Near threatened
Macaroni penguin	1,000,000	Decreasing	Vulnerable
Rockhopper penguin	10,000	Decreasing	Vulnerable
Wandering albatross	1	May be attempting to recolonise	Vulnerable
Black-browed albatross	~600	Increasing	

Fluctuations in species' populations have been observed on other sub-Antarctic islands, but these could be due to a range of factors (E Woehler 2006, pers. comm.). On Heard Island, for example, glacial retreat has allowed some species to effectively colonise bare ground that would have otherwise been extensively covered with ice. A continued warming trend is likely to further impact on species distribution and abundance in a way that is difficult to predict. Impacts on oceanic food sources appear the most likely way the species will be impacted.

Populations of invertebrate species, some endemic to Heard and McDonald Islands, and some endemic to the Heard and McDonald Islands/Kerguelen region.

Heard Island has few endemic invertebrate species, in comparison to other Southern Ocean islands (Chown et al. 2006). Although many insect population expansions are documented (Thost 2001), the results of numerous quantitative surveys have yet to determine the extent of expansion and distribution of most species (Chown et al. 2006). Comparisons of identical mite species assemblages on Heard and Marion islands suggest that their habitat distributions, relative to the Antarctic Polar Frontal Zone, are basically the same, despite the differences in climate and glacial retreat between the two islands (Marshall & Chown 2002). The effect of temperature extremes on sub-Antarctic weevils has also received some attention in recent years (Klok & Chown 2003). The results of this study showed that tolerances to minimum and maximum temperature varied between the *Ectemnorhinus* group of weevil species, but was due to species' plasticity rather than adaptive change (Klok & Chown 2003).

55 Estimated 80,000 pairs in 2004 (Wohler, <http://data.aad.gov.au/aadc/soe/display_indicator.cfm?soe_id=30>)

Laurens Peninsula and the lower snow-covered slopes of Anzac Park. *Australian Antarctic Division*

Invertebrate fauna on Heard Island is regarded as near pristine. There is only one alien thrip (*Apterothrips apteri*), one mite (*Tyrophagus putrescentiae*) (Frenot et al. 2005) and one alien worm species (*Dendrodrilus rubidus*) (Dartnall 2003). However, future introductions of alien species may occur (Chown et al. 2006). There is a strong relationship between the frequency of human visitation and introductions of alien species on Southern Ocean islands (Chown et al. 1998). Climate warming is likely to increase the probability of alien species becoming established, and may also exacerbate the invasive impacts of alien species that do become established (Chown et al. 2006).

Populations of seal species, including breeding southern elephant seals, Antarctic and sub-Antarctic fur seals.

Global climate change may affect seal populations through changes in primary and secondary production, and water circulation (Australian National Committee on Antarctic Research 2006).

Five species of true seals (Phocidae) and two species of eared seals (Otariidae) occur on the islands. Of these, numbers of Antarctic fur seals have been rising significantly (Green 2006) but trends are not presently clear. Fur seals (*Arctocephalus gazelle*) were hunted to near extinction in the 19th century (Shaugnessy et al. 1988), and fur seal pups were not subsequently born on Heard Island until 1963 (Budd & Downes 1969). The most recent (2000–2001) census of Antarctic fur seals estimated a breeding population of just over 4,000, a fourfold increase in fur seals since the 1987–1988 survey (Page et al. 2003). The number of fur seals on Heard Island was expected to continue to expand until either food availability or breeding space limits pup production (Page et al. 2003). However, a decline in pupping rates of land-breeding seals on Heard Island has been observed, coinciding with an increase in sea surface temperatures north of the islands over the past 15 years (Australian National Committee on Antarctic Research 2006).

After recovering well from early population declines associated with exploitation, southern elephant seal (*Mirounga leonine*) populations on Heard and McDonald Islands declined by about half between the 1950s and the 1980s (Green 2006), perhaps due to a change in the abundance and availability of food (McMahon et al. 2005) thought to be associated with wide-scale changes in the Southern Ocean beginning in the mid-1960s (Australian National Committee on Antarctic Research 2006). Although numbers are currently stable (Australian National Committee on Antarctic Research 2006), McMahon and Burton (2005) concluded on the basis of maternal energetic studies that southern elephant seal populations are likely to be negatively affected by the warming of sea surface temperatures predicted with climate change. Antarctic krill (*Euphausia superba*) stocks in the southern ocean have declined since the 1970s, possibly due to a contraction in the extent of sea ice, due to warmer ocean temperatures (Atkinson et al. 2004). Further decline in the population is a likely scenario under the influence of continued global warming.

Species of conservation significance (such as the endemic Heard shag (*Phalacrocorax nivalis*) and the endemic sub-species Heard Island sheathbill (*Chionis minor nasicornis*).

The endemic Heard shag (*Phalacrocorax nivalis*) is threatened due to its small population size and limited distribution. The high mortality rate and poor breeding success of the Heard Island population has been attributed to severe weather (Pemberton & Gales 1987) and may make this species more vulnerable to climate change impacts. However, despite a history of high mortality, recent discovery of a colony of 1,000 breeding pairs means that the endemic Heard shag population is larger than previously thought (E Woehler 2006, pers. comm.). The Heard shag is not threatened by introduced predators, as has been the case of a related species on Macquarie Island where cats (now eradicated) previously threatened the survival of Macquarie shag chicks (Selkirk et al. 1990).

Changes in sea temperature and therefore food supply could adversely affect all seabird species, including the Heard Island sheathbill; and albatrosses, penguins and a range of petrel species (Chambers et al. 2005).

Absence of human disturbance, providing unique opportunities for research into population dynamics of plant and animal species.

Heard and McDonald Islands are largely unaffected by human disturbance, and they provide a unique opportunity to collect baseline data on the response of species to climate change in the near absence of other anthropogenic influences (e.g. land clearing, alien invasive species, urban development). However, human visitors to the islands increase the risk of introduction of non-indigenous species (Chown et al. 1998), and warming trends increase the chance of survival of newly introduced species.

8.12.4 Associated threats

Heard Island has only three terrestrial species classified as non-indigenous or alien (Frenot et al. 2005) and none are recorded from the McDonald Islands. The only recorded alien plant species, *Poa annua*, expanded dramatically on Heard Island between 1987 and 2000. This is correlated with an increase in seal disturbance, but also appears to be influenced by climatic change (Scott & Kirkpatrick 2005). Introduction of further invasive alien species is one of the largest threats to conservation of the island's biodiversity values, and rising temperatures may facilitate their establishment and spread if they are introduced accidentally (Scott & Bergstrom 2006). Chown (2003) provided an outline of risks and mitigation strategies for non-indigenous species on Heard and McDonald Islands.

8.12.5 Gaps in knowledge and future directions

The Heard and McDonald Islands are managed under the *Heard and McDonald Islands Marine Reserve Management Plan* (Commonwealth of Australia 2005). This plan identifies climate change as a key issue, both as a driver of change to environmental values and of research to understand the consequences of climate warming. It details a range of research and monitoring priorities required to gain an improved understanding of climate change effects, as well as a range of practical management actions to protect the islands' World Heritage values.

Brown Glacier, Heard Island. *Chris Stevenson*

Examples of research priorities identified in the management plan of particular importance in the context of climate change include:

- the development of climate change scenarios for this World Heritage property (highly recommended)
- monitoring of changes to the coastline, glacial landscape and other features of the islands, including the area and extent of newly deglaciated land
- monitoring of changes in the composition and extent of vegetation communities, and the colonisation of newly deglaciated land by plants and animals
- surveys to increase knowledge of the biodiversity of the islands, and of its responses to climate change. There is a particular need to monitor trends in population numbers and association of these with changes to food and other habitat elements
- long-term climate monitoring
- where practical, remote sensing of vegetation, glacial retreat, benthic communities, and habitats and other features
- comprehensive surveys of indigenous species to provide baseline information enabling quantification of new introductions of terrestrial, freshwater and marine species, and enforcement of stringent quarantine measures to reduce the risk of alien invasive species introductions
- continued assembly of an historical account of landscape changes, derived from photographs and drawings, to illustrate climate change impact
- development of new methods for measuring glacial retreat in past, present and future climates. This may enable the behaviour of unobserved glaciers to be determined. Elucidation of the overall pattern of response to recent and decadal climate change variations, and also to climate fluctuations which occurred before the 20th century, may also be possible (Ruddell 2006). Modelling techniques using remote sensing will provide reliable estimates of snow accumulation and ablation, which are otherwise difficult to obtain (Ruddell 2006).

8.13 Macquarie Island

View from North Head to the southern part of the island. *Mike Preece*

8.13.1 Climate change scenarios for Macquarie Island

- The average annual temperature for this World Heritage property is expected to increase by +1.1 °C ± 0.2 °C by 2030, based on the climate change scenarios for Tasmania relative to 1990 and on a 'high' greenhouse gas emissions scenario.[56]
- Sea level is expected to rise by about 17 cm under a 'high' greenhouse gas emissions scenario.[57]

8.13.2 Summary of impacts

Macquarie Island (54°30'S, 158°57'E) is situated just north of the Polar Front and about 1,500 km south-east of the Australian mainland. It has an area of about 124 km^2. There has been an increase in annual mean temperature of about 1 °C since 1949 (Selkirk 1992). Records show summer temperatures on the island have been increasing since the 1950s (Adamson et al. 1988; Selkirk 1992), warming 0.4 °C from 1951 to 2006 (National Climate Centre, Bureau of Meteorology, pers. comm.; Tweedie & Bergstrom 2000), along with increases in wind speed, precipitation and evapotranspiration, and decreases in air moisture content and sunshine hours since 1950 (Frenot et al. 2005).

Tectonic activity is likely to continue. Higher sea surface temperatures and a decrease in the extent of the Antarctic sea-ice sheet could be affecting the availability of food for the top marine predators. Rockhopper penguin populations will probably decline. Global warming could result in distributional changes of the vegetation, and a contraction of the area of peat systems and sphagnum moss beds. Rabbits and introduced plant pests are modifying the island's vegetation and significantly affecting seabird breeding habitat.

56 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

57 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

8.13.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criteria

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Values include:

Seafloor spreading and other geological tectonic processes (oceanic crust formed by seafloor spreading).[58]

Macquarie Island is a Tasmanian State Reserve managed by Tasmania's Parks and Wildlife Service. It lies on a section of the earth's crust at the boundary between the Pacific and Australian tectonic plates, which is uplifting as a result of tectonic processes. It is the only exposed section of the Macquarie Ridge Complex. Tectonic uplift is still occurring.

Sea level change, in response to glacial and interglacial conditions, also influences the movement of the earth's crust as large volumes of water are transferred between the ice sheets and the ocean (Lambeck et al. 2002; Lambeck & Chappell 2001). During deglaciation there is a change in the land surface load, resulting in a slow rebound of the earth's crust, or lithosphere, known as glacial-hydro-isostatic rebound (Lambeck et al. 2002).

Sea floor subsidence (hydro-isostasy) can also occur during deglaciation, when the extra volume of water from the melted sheet ice increases the surface load on the ocean floor (Woodroffe & Horton 2005). A sea level rise of 100 m imposes a surface load in the order of 100 t/m^2 (Lambeck et al. 2002; Woodroffe & Horton 2005). In tectonically active regions, isostatic processes can result in neotectonic deformation or movement of the earth's crust (Woodroffe & Horton 2005).

Tectonic uplifting has occurred for millions of years. It is a continual process, but it is also episodic (I Houshold 2006, pers. comm.). A major earthquake near the island in 2004 resulted in the horizontal displacement of the island (P Tregoning 2006, pers. comm.). The effect of sea level rise on geological tectonic processes is largely unknown. A GPS network on the northern section of the island, to monitor the rate of tectonic uplift, is managed by Geoscience Australia.

Lake systems, tarns and pools.

There are numerous pools, tarns and lakes situated on the island's raised beach terrace and plateau, the largest of which is Major Lake (Parks and Wildlife Service 2003). Sea level fluctuation, and the actions of wind and water, have eroded sections of the island's escarpment, allowing water to drain from some of the lakes (Parks and Wildlife Service 2003). Most streams and pools are normally alkaline and only a few centimeters deep (Croome 1984; Selkirk et al. 1990). The composition of the lake and pool water is largely determined by sea-spray drift and deposition (Mallis 1988).

Stream invertebrate fauna represent a diverse range of taxonomic groups (Dartnall et al. 2005; Marchant & Lillywhite 1994), including aquatic insects (e.g. *Plecoptera*, *Ephemeroptera* and *Trichoptera*) with poor dispersion capabilities. Diatoms represent a large proportion of the freshwater biota (Van de Vijver & Beyens 1999).

58 An ophiolite is any of a group of igneous and metamorphic rocks found within the continental crust, thought to be formed by the uplift of oceanic crust.

Mosses. *Noel Carmichael, Tasmanian Parks & Wildlife*

Fundamental changes in the limnology of sub-Antarctic lakes and ponds are likely as a result of global climate warming (Wrona et al. 2005). Characteristics such as ice cover, pH, nutrient composition, organic carbon, and sediment loads in lakes and pools, are likely to exhibit varying degrees of change in response to changing climatic conditions. Small tarns and shallow pools are likely to become more vulnerable to the effects of global warming than are lakes or large water bodies (Smol et al. 1991). As a result, trophic interactions and the productivity of these systems are also likely to change (Douglas & Smol 2000), accompanied by acceleration in the rate of decomposition of organic matter and an increase in nutrient cycling (Rouse et al. 1997). Extension of the ice-free season of waterbodies will be a consequence of higher temperatures, which will also increase the length of the period of temperature-induced stratification with deeper mixing (Rouse et al. 1997). Higher levels of UV-B exposure could also threaten the ecology of freshwater ecosystems of Antarctic and Arctic biomes (Vincent & Pienitz 1996; Wrona et al. 2005).

Dramatic changes in vegetation cover due to climatic conditions. Extensive peat beds.

Macquarie Island's vegetation has been well surveyed and studied over the past 50 years. Vegetation communities on the island consists of herbs, grasses and prostrate species and include herbfields, fernbrakes, feldmark, mires, tussock grasses and cushion plants (Selkirk et al. 1990). A small prostrate shrub, *Comprosma pumila*, is the only shrub species inhabiting the island. The island also contains large numbers of non-vascular plants, such as bryophytes and lichens (Selkirk 1992).

Selkirk (1992) expects that, as temperatures increase, there will be a higher rate of photosynthetic activity and productivity in most plant species on the island. Several plant species on the island have optimum temperatures for photosynthesis that are well above the current ambient temperature. Climate change is likely to create conditions more suitable for some species than others. Small-scale distributional changes (mainly expansion) have been observed in two species of vascular plants, *Carex trifida* and *Poa litorosa*, with further changes likely to continue in response to a warming climate (Bergstrom et al. 2006). Conditions could become suitable for woody vegetation within 100 years if temperatures continue to rise at the current rate (Selkirk 1992).

Litter decomposition rates in cold biomes will increase with global warming, providing there is sufficient soil moisture (Aerts 2006). Peat systems could contract with global warming if the dynamics of the system change from a carbon sink to a carbon source, due to an increase in bacterial and fungal decomposition (Rouse et al. 1997). Changes in vegetation composition within peat communities and the sequestration of carbon are highly influenced by the water budget (Belyea & Malmer 2004). Further global warming and reduced precipitation could result in a dramatic change in peat systems on Macquarie Island.

Higher temperatures and lower humidity have had a negative impact on the growth of some plant species, such as *Sphagnum falcatulum* (a moss). This species is the only *Sphagnum* species on the island, but it also occurs on other sub-Antarctic islands as well as on mainland Australia (Seppelt 2000). A combination of above-average temperatures, low precipitation and a decline in humidity between April 1999 and May 2000 caused the destruction of many of the island's small, shallow sphagnum beds. Although *Sphagnum falcatulum* grows extensively on the island, current climatic conditions are marginal for its growth and sphagnum moss beds are expected to gradually decline as the result of climate change in this region (Whinam & Copson 2006).

Penguin communities including rockhopper, king and royal penguins.

Macquarie Island provides habitat for king (*Aptenodytes patagonicus*), gentoo (*Pygoscelis papua*), royal (*Eudyptes schlegeli*) and rockhopper (*Eudyptes chrysocome*) penguins. *Eudyptes schlegeli* is endemic to the island.

Birdlife International (2004) lists 25 globally endangered bird species (out of a total of 1,215) most likely to be threatened by climate change. Six of the 25 most threatened species belong to the penguin genus *Eudyptes*, which includes the rockhopper (*Eudyptes chrysocome*). The island's rockhopper penguin population appears to be stable, but exact numbers are difficult to determine (Parks and Wildlife Service 2003). Rockhopper penguin populations on Campbell, Falklands, Heard and Antipodes islands show a substantial decline in population numbers (Ellis et al. 1998). The cause for these declines is unknown (E Woehler 2006, pers. comm.).

Penguins are a highly specialised group, relying on a relative abundance of prey for survival and reproductive success. Changes in sea surface temperatures and a decline in food resources could be contributing to the decline of some penguin populations (i.e. rockhopper penguins) in the sub-Antarctic region (Cuthbert & Sommer 2004; Thompson & Sagar 2002). Several penguin studies have linked these declines to a decrease in food production associated with rising sea temperatures (Cunningham & Moors 1994; Guinard et al. 1998). A recent study supported the hypothesis that population decline in rockhopper penguins is closely associated with a shift towards lower food production, but it failed to find a clear correlation between population declines and a shift towards higher temperatures (Hilton et al. 2006).

Majestic albatross nesting on cliffs which are easily viewed.

The wandering albatross (*Diomedea exulans*) and grey-headed albatross (*Thalassarche chrysostoma*) are listed under the *Environment Protection and Biodiversity Conservation Act 1999* [59] as vulnerable to extinction. Pelagic long-line fishing is a major threat to these birds (Brothers 1991; Gales 1998), causing a decline in their numbers around the world (Birdlife International 2004). Research on Macquarie Island shows that the survival rates of the black-browed albatross (*Thalassarche melanophrys*) and the grey-headed albatross have remained relatively unchanged since the 1970s (Terauds et al. 2005). Fishing, rather than climate change, poses the greatest threat to the survival of these birds. However, avian cholera in albatross and large petrel populations could become a greater threat with continued global warming (Weimerskirch 2004).

Albatross spend a considerable amount of time in waters outside the marine protected areas, which exposes them to greater risk from fishing activity (Terauds et al. 2006). Black-browed and grey-headed albatross populations could face considerable risk from fishing activity in the future, even though it is unlikely that a substantial reduction in population numbers has been caused by past fishing activity (Terauds et al. 2005). However, a significant decrease in the survival of particularly juvenile wandering albatrosses coincided with an increase in the activities of long-line fishing vessels (Terauds et al. 2006).

59 <http://www.environment.gov.au/epbc/index.html>

West Beach. *Melinda Brouwer and the Department of the Environment, Water, Heritage and the Arts*

Impressive colonies of elephant seals.

The southern elephant seal (*Mirounga leonina*) population recovered after exploitation ceased in the 1920s. About 155,000 animals were estimated to be present on the island in the 1950s (Parks and Wildlife Service 2003). However, their numbers have declined since the 1960s, at a rate of about 1.2% per year. In 2002 it was estimated that population numbers had declined to less than 50% of the 1950s population (Parks and Wildlife Service 2003).

Various explanations for the southern elephant seal population decline have been advanced (McMahon et al. 2005). A large and widespread decline in population is often an indication of an underlying change in the ecosystem at large (Caughley & Gunn 1996; McMahon et al. 2005). The most plausible explanation for the decline is a change in the abundance or availability of food associated with shifts in the Antarctic Circumpolar Wave (ACW) and the ENSO cycle (McMahon et al. 2005; Murphy & Reid 2001). ENSO influences the extent of sea-ice retreat (Kwok & Comiso 2002), which in turn affects the survival and recruitment of krill (Loeb et al. 1997). It is unclear how the frequency and intensity of El Niño events will respond to global warming.

These studies suggest that changes in sea surface temperature and ambient air temperature are influencing the biology of top marine predators, either directly or indirectly, via changes in food abundance and distribution. However, despite the growing body of supporting evidence, the interactions are still poorly understood.

8.13.4 Associated threats

Invasive species have particularly significant impacts on islands. They prey on predator-naïve island populations, out-compete many indigenous species for food and space, and change the structure of the vegetation with consequential habitat impacts on other native species. Several vertebrate pests became established over the past two centuries on Macquarie

Island. These included rats, cats and European rabbits (Copson & Whinam 2001). Cats have now been eradicated (success declared in 2002) and rabbits are the next target species for eradication.

Rabbits inflicted substantial damage to the island's native vegetation as the rabbit population expanded (K Kiefer 2006, pers. comm.). One of the results has been a significant loss of vegetation and habitat for breeding seabirds due to increase in rabbit numbers. A jointly-funded Commonwealth/state rabbit and rodent eradication plan is currently being implemented.

Ship rats (*Rattus rattus*) are also widespread on the island and commonly feed on the shoots of *Poa foliosa* (Copson & Whinam 2001). There is also unsubstantiated evidence that rats are feeding on the eggs and chicks of burrow-nesting petrels (Shaw et al. 2005). The potential for further expansion of rats following the removal of rabbits and with amelioration of the local climate with climate change is not known.

Introduced plants such as *Poa annua*, *Cerastium fontanum* and *Stellaria media* are widespread (Parks and Wildlife Service 2003), but do not currently occur in extensive populations, except for *Poa annua* in areas heavily grazed by rabbits (D Bergstrom, pers comm.). However, other species such as *Anthoxanthum odoratum* and *Rumex crispus*, which occurred in local pockets, have been successfully removed (Copson & Whinam 2001). Impacts of climate change on these species are not known.

Recruitment to the island of other pests and disease is likely to pose an increased risk as a result of global climate change, and hence pose a major threat to the island's biodiversity values. Introduced species already present as 'sleeper populations' have the potential to expand and become a problem as conditions become more suitable for them under climate change. The potential for the spread and outbreak of disease, and the mass expansion of pests in the Southern Ocean resulting from global warming, is well documented (Bergstrom & Chown 1999; Frenot et al. 2005; Shaw et al. 2005; Smith et al. 2002; Weimerskirch 2004).

8.13.5 Gaps in knowledge and future directions

- The effects of sea level rise on tectonic activity are currently unknown.
- Although insect and microbial activity is likely to increase with increasing temperature, it is uncertain what long-term impact this will have on the nature of island ecosystems. There have been very few studies of the rates of decomposition of cold-adapted species in these environments.
- Climate data are not good for the island. The development of good data monitoring systems and climate change scenarios is recommended.
- Although some fundamental changes in the limnology of lakes, tarns and pools will occur with higher temperatures and increased UV-B exposure, the long-term impacts on the island's ecology and on World Heritage values are difficult to predict.
- The impact of climate change on plant species has received little attention in recent years and requires further investigation. *Sphagnum* moss has often been used as an indicator species for climate change throughout the world (IPCC 2001), and could fulfil this role on the island.
- The capacity of rockhopper penguins to maintain population numbers, and for king penguins to increase the size of their population, is unclear and requires further investigation. Several studies link rockhopper penguin declines on other sub-Antarctic islands to a change in food production correlated with a change in the extent of sea ice.
- The effects of rising sea surface temperatures on sheet ice contraction and food supply requires further research. The interactions between ENSO activity, rising temperatures and changes in food supply are largely unknown.
- Further research is required into those endemic, iconic and threatened species of Macquarie Island that are most likely to be at risk from climate change.

8.14 Greater Blue Mountains Area

Mount Solitary, from Echo Point. *Mark Mohell and the Department of the Environment, Water, Heritage and the Arts*

8.14.1 Climate change scenarios for New South Wales

The following climate change scenarios for New South Wales, relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[60]

- Average annual temperature is expected to rise 1.3 °C ± 0.6 °C by 2030, with an increase in the number of hot days.
- While average annual rainfall is considered unlikely to change, seasonality is anticipated to change with more strongly decreased rainfall in winter and spring, and mildly increased rainfall in summer and autumn.
- Higher evaporative demand (5.6% ± 4.4%) is likely to reduce runoff into streams and rivers.
- Extreme weather events are likely to result in flash flooding.
- Droughts, and the number of days of extreme fire danger (projected to increase by 10 days per annum), are likely to increase in frequency, increasing the risk of severe fire events (Hennessy et al. 2006).

8.14.2 Summary of impacts

Greater Blue Mountains Area covers an area of 1.03 million hectares, and consists of eight protected areas and national parks. Australia's south-eastern temperate forests, which include the Greater Blue Mountains, are regarded as the world's most fire-prone regions (Cunningham 1984). Fire is a major threat to this World Heritage property. More severe and frequent drought is likely to increase the number of days of high-to-extreme fire danger (Hennessy et al. 2006; Williams et al. 2001;

60 60 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

Williams et al. in press). Variable rainfall, drought, strong winds and changeable weather conditions—in combination with highly flammable vegetation—create ideal conditions for extreme and variable fire behaviour (Coates 1996). A rise in temperature, as well as a change in the frequency and intensity of forest fires, may have an effect on both vegetation and fauna of the region.

8.14.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criteria

Criterion (ix): To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Criterion (x): To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Values include:

Major eucalypt groups, plant taxa with very high levels of species diversity.

Greater Blue Mountains Area contains an exceptional representation of major eucalypt groups, including taxa exhibiting high levels of hybridisation and exceptional diversity. There are 100 eucalyptus species present, representing over 14% of the global total. The greatest threats to eucalyptus species from global climate change are rising temperature and changing fire regimes.

The expected change in the geographical distribution of 830 eucalypt species in response to rising global temperatures was modelled by Hughes et al. (1996). This study showed that 53% of eucalypt species occupy a temperature range of less than 3 °C and 41% have a temperature range of less than 2 °C. A temperature rise of 1–2 °C will shift many eucalypt species out of their current climatic envelope. Pouliquen-Young and Newman (2000) used the BIOCLIM [61] climate modelling system to estimate that a 1°C rise in temperature could result in a 59% loss of the bioclime of acacia species.

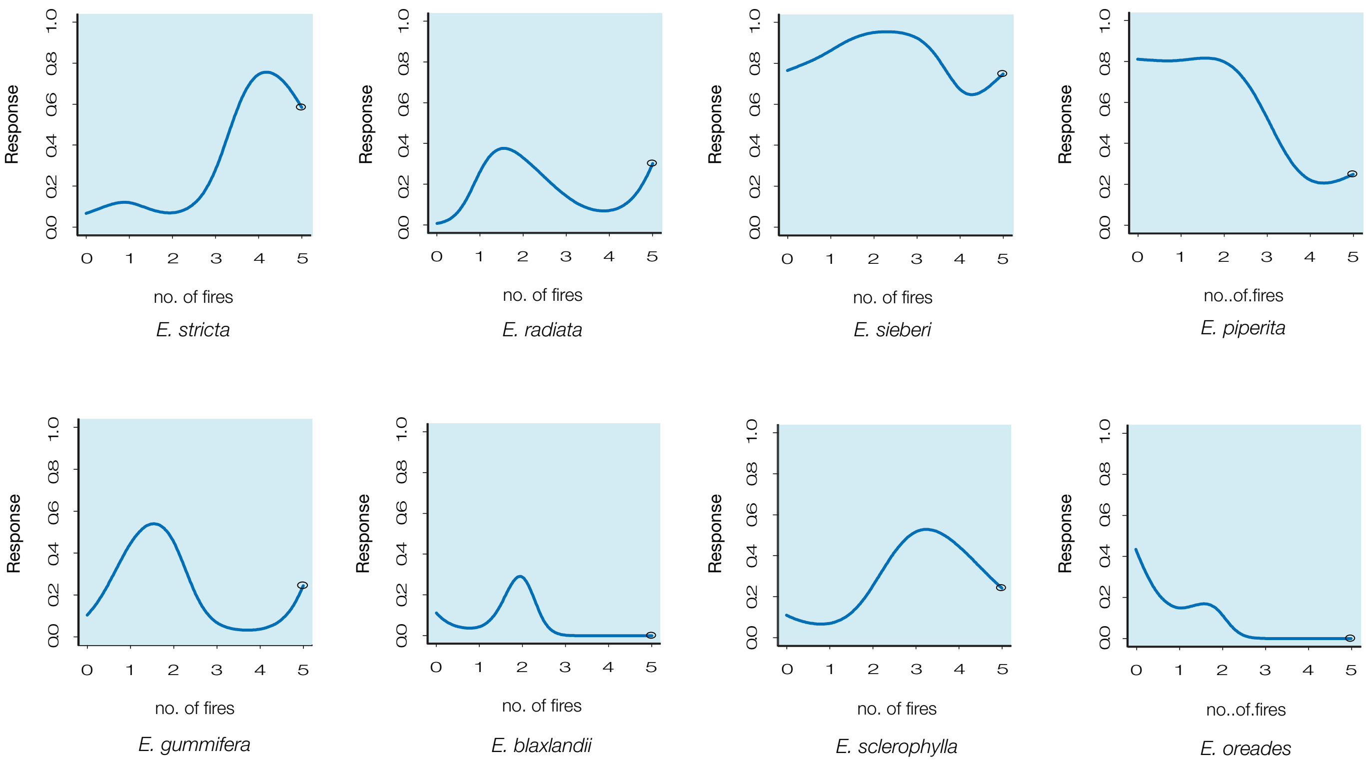
Phenological studies of eucalypts show variations in flowering time in response to long-term changes in temperature and rainfall (Keatley et al. 2002). An increase in temperature and summer rainfall is likely to influence the commencement date of flowering for a range of eucalypts, resulting in later flowering times for some species (e.g. *Eucalyptus microcarpus* and *E. polyanthemos*).

Fire is an essential part of the eucalyptus life cycle, but some Mallee ash eucalypts (*Eucalyptus obstans*, *E. luehmanniana*, *E. burgessiana* and *E. rupicola*) require fire-free periods of six years or more to ensure their survival (Auld et al. 1993). Although fire is a driver for eucalypt vegetation expansion and adaptation, changed forest fire regimes may result in the irreversible loss of some species. A recent study (Ku 2006) identified several eucalypt species in the Greater Blue Mountains Area that are highly sensitive to an increased frequency of extreme fire events. Several species (*E. piperita*, *E. eugenoides* and *E. blaxlandii*) and an obligate seeder [62] (*E. oreades)* could face extinction from more frequent and extreme fire events. In contrast, other species, such as *E. stricta*, *E. radiata* and *E. sclerophylla*, showed a marked positive response to moderate fire frequency (i.e. four to five fires in 50 years). The response of these species to increased fire is summarised in Figure 9.

61 Reference: <http://cres.anu.edu.au/outputs/anuclim/doc/bioclim.html>

62 Relying on seed production for regeneration.

Figure 9. Response of eucalyptus species to fire frequency (Source: Ku 2006)



Intense wildfires can significantly reduce vegetation cover and accelerate erosion (Shakesby et al. 2003). Mosaic burning is already being used by the property's managers to reduce excessive fuel loads and minimise the threat of destructive wildfires (Merson 2006). However, controlled burning cannot be regarded as a panacea for wildfire control or prevention, as it can also result in significant landscape and ecological disturbance, including the potential for accelerated runoff and soil loss (Gyasi-Agyei 2006). Studies that have examined the impacts of prescribed burning on vegetation type are also documented (Bradstock & Kenny 2003; Bradstock et al. 1998).

The impact of future climate change and fire on plant communities is unknown. There are few systematic studies undertaken in the Greater Blue Mountains specifically examining the impact of fire on vegetation (Hammill & Bradstock 2006). Information on the relationship between fire and plant species' vulnerability comes from prior studies undertaken in coastal regions of New South Wales. Although the Greater Blue Mountains sandstone landscape supports plant communities of similar origin to the sclerophyll forests and open woodlands of coastal regions, there are significant differences in the climates of these regions (Keith & Benson 1988). These differences influence the distribution of species and they may also influence the response of plant communities to fire (Hammill & Bradstock 2006). A planned three-year study by the NSW Department of Environment and Climate Change will attempt to systematically determine the effects of fire history and climate on vegetation composition in the Greater Blue Mountains.

Obligate seeders (species that rely entirely on seed production for reproduction) are particularly sensitive to frequent fire events (Bradstock et al. 1996). Fire–vegetation studies show that extinction of *Banksia* populations is likely if a succession of fire events occurs during the juvenile stages of plant development.

Mediterranean climate, including plateau tops, ridges, exposed rocks, cliffs, rocky slopes and sheltered gorge, valley and karst systems.

A distinctive feature of the Greater Blue Mountains is the geodiversity—the variety of plateau tops, ridges, exposed rocks, cliffs and rocky slopes. Geodiversity is vulnerable to climate change impacts in that it is vulnerable to all forms of fire, including hazard reduction burns and backburns, as well as wildfires. Rocky habitats may also be vulnerable to rock instability caused by wildfires.

Sandstone outcrops and rocky cliff faces are more likely to become weak and brittle from the extreme heat generated by intense fire storms, predisposing these natural features of the landscape to fire-induced rock weathering (Shakesby & Doerr 2006) such as spalling (flaking) (Christensen 1994). Measurements conducted in the Greater Blue Mountains show that spalling can result in up to 6 g of dislodged rock per square metre of fire-exposed sandstone (Adamson et al. 1983). Humphreys et al. (2003) estimated sandstone denudation rates of about 3 g/m^2/yr.

Heat from fire can also lead to the deterioration of the karst environments in the Greater Blue Mountains, by stimulating erosion and changes to chemical processes. In still conditions, the temperature at the base of flames can easily reach 750 °C (CSIRO 2001). At these temperatures, limestone undergoes a chemical process (calcination) unique to carbonate stone, resulting in complete disintegration of exposed surfaces (Holland 1994). The purity of the limestone and the temperature of the fire determine the extent of cracking, spalling and calcination.

Weakened stone, combined with a loss of vegetation, can lead to erosion of karst, resulting in the loss of organic surface soils and/or peat. These fire-affected landscapes have the potential to change the hydrology of the underlying karst. The sedimentation of waterways (e.g. the Jenolan River) may also occur due to erosion, and has the potential to reduce water quality, which affects aquatic species.

Increases in fire frequency may also result in rapid, irreversible destruction of surface karst features, and alter chemical and hydrological processes on which cave speleothems (chemical deposits, such as stalactites) and invertebrates rely.

Species with Gondwanan affinities that are of outstanding significance in terms of the evolution of plant life, including the Wollemi pine (*Wollemia nobilis*) and the primitive gymnosperm *Microstrobus fitzgeraldii.*

Greater Blue Mountains Area has over 70 plant communities, including 56 open forest and woodland communities, forming a landscape dominated by eucalypts. Wet environments, such as rainforests, are also present. The rainforests of the Greater Blue Mountains provide a microclimate for primitive plant species with Gondwanan affinities such as *Lomatia*, *Dracophyllum* and *Podocarpus*. These Gondwanan affinities have specific microclimatic requirements. The deep valleys and crevasses, flanked by rugged perpendicular cliff faces, provide protection against high winds and fire. However, it is uncertain whether these specific terrain characteristics will continue to provide protection against more extreme fire events.

The Wollemi pine (*Wollemia nobilis*) is a unique species with a Gondwanan affinity, currently restricted to a few undisclosed specialised habitats in rainforest communities in deep sandstone gorges in the Wollemi National Park part of the Greater Blue Mountains. This species, originally thought to be extinct, has survived in this environment for over 100 million years (Briggs 2000). Pollen evidence shows the wollemi pine has been steadily declining since 65–34 million years ago in response to cooling and drying during the northward movement of Australia. The wet microhabitats in which it is found are refugia for species that are not tolerant to drought, or to high fire frequencies or intensities, because they are sheltered from the hot, dry, fire-prone conditions of the surrounding forest and woodland (NSW DECC 2006). As future climate projections for New South Wales are for continuation of the current drying trend, together with ongoing warming, the species may be threatened by changes to its known habitat by climate change but the vulnerability of this species is unknown. Bioclimatic/GIS modelling is being used to locate sites that may serve as climate refugia in the future (NSW DECC 2006).

Mt Hay bushfire, Blue Mountains National Park. *Ian Brown (NSW National Parks and Wildlife Service)*

High level of diversity of invertebrate fauna, and animal taxa of conservation significance.

Greater Blue Mountains Area is habitat to about 400 vertebrate taxa—265 bird species (representing 33% of Australia's total bird population), 63 reptile species, more than 30 frog species, and 52 species of native mammals including species of global significance such as the platypus (*Ornithorhynchus anatinus*) and the echidna (*Tachyglossus aculeatus*).

The most notable invertebrate taxa are the Lepidoptera (of which there are about 4,000 moth and 120 butterfly species) and the cave-dwelling taxa in the Jenolan Caves. Insects typically respond to climate change by migrating to more climatically favourable regions where they can (Hill et al. 2002). However, some species are incapable of relocating to more favourable regions. Beaumont and Hughes (2002) identified 77 butterfly species endemic to Australia with wide climatic ranges in comparison to other invertebrate taxa, with only 8% having a mean annual temperature range of 3 °C or lower. However, many species could be at risk, even from a temperature rise of 0.8–1.4 °C by 2050 (Beaumont & Hughes 2002).

Greater Blue Mountains Area has 10 karst environments. One hundred and twenty six species of cave-dwelling invertebrates have been identified in one of the sites, the Jenolan Karst Conservation Reserve (Thurgate et al. 2001). The number of species at the remaining nine sites has yet to be confirmed. Some of the invertebrates found in caves are highly adapted, and totally reliant on the cave environment. Consequently, any change in environmental conditions may be potentially fatal, due to the inability of these species to migrate. Small, artificially induced changes in cave temperature and humidity within a single cave chamber resulted in rapid abandonment by cave-dwelling invertebrates (Howarth 1988). It is likely that many cave-dwelling invertebrates will not adapt to, or survive, increases in cave temperatures occurring as a result of climate change.

Myrtaceae provide habitat for a wide range of invertebrate and vertebrate species. The impact of fire and temperature on vegetation cover, discussed previously, are likely to have flow-on effects for many vertebrate and invertebrate populations. The relationship between habitat cover and its impact on species richness is well documented (Andren 1994; Pausas et al. 1997; Rolstad & Wegge 1987; With & King 1999).

Dynamic habitat models show that changes in the native eucalypt vegetation cover can impact on faunal richness (Pausas et al. 1997). For example, the regent honeyeater (*Xanthomyza phrygia*) has very specific nesting requirements, preferring to nest in yellow box/red gum/ironbark woodlands. These woodlands are extremely rare in many areas of the Greater Blue Mountains, especially in Wollemi National Park (DEC 2005). The threshold response of many species to changes in vegetation cover following environmental disturbance is not well understood, and is an area requiring further investigation (Lindenmayer et al. 2005).

Elevated atmospheric CO_2 concentrations can cause plant metabolic changes, resulting in an increase in the synthesis of leaf tannins and phenolics, and other chemical changes with impacts on nutritional value and palatability of leaves (Curtis & Wang 1998; Hume 1999; Koricheva et al. 1998). These chemical changes have the potential to affect the growth rates and survival of arboreal leaf-eating species (Hume 1999; Kanowski 2001).

About 33% of Australian bird species have been recorded in the Greater Blue Mountains. Studies investigating the relationship between climate change and bird fauna have been confined mainly to the northern hemisphere. Australia's most comprehensive study of the effect of climate change on avifauna (Bennett et al. 1991) simulated the effects of temperature and rainfall changes on the distribution of the bioclimates of Victorian birds (including the swift parrot (*Lathamus discolor*), sooty owl (*Tyto tenebricosa*) and the regent honeyeater (*Xanthomyza phrygia*), which are also found in the Greater Blue Mountains). It showed that a decrease in the distribution of the bioclimates of all species resulted from a 3 °C temperature rise and a 10% decrease in rainfall. This is a realistic climate change scenario for the south-eastern region of Australia. The assumptions made in this study are summarised in a review by Chambers et al. (2005).

Greater Blue Mountains Area is habitat to species of global significance such as the platypus (*Ornithorhynchus anatinus*) and the echidna (*Tachyglossus aculeatus*). Although these animals are classed as mammals, they have some reproductive traits similar to reptiles, including the laying of eggs. The platypus is highly dependent on the quality of the streamflow environment, and burrows to provide protection against the extremes of ambient temperature (Scott & Grant 1997). The removal of riparian vegetation can lead to erosion of streambanks and a reduction in the number of suitable burrow sites. In addition, increased water turbidity can also reduce production of food for platypus populations (Scott & Grant 1997). More severe and longer periods of drought, with a subsequent reduction in runoff into streams and rivers (CSIRO 2006), will reduce suitable habitat for this species. A reduction in stream flow would reduce foraging area and affect reproduction during the breeding season (Grant et al. 1983).

8.14.4 Associated threats

The Wollemi pine is susceptible to a range of introduced pathogens, including *Phytophthora cinnamomi*, a soil-borne water mould. Climate change may provide more favourable conditions for the survival of a range of pathogens. Feral animals and weeds are also a significant problem that may be compounded by climate change.

An increase in the frequency of forest fires initiated by anthropogenic ignitions (e.g. arson, traffic accidents, campfires), rather than from natural causes such as lightning strikes, is a significant threat. There is a strong relationship between urban expansion and increased wildfire frequency (Keeley et al. 2004). The construction of new roads and further urban expansion, in association with continued climate change, will exacerbate fire-related problems. The impact of climate change on fire ignition sources and rates is not known.

Lake Couridjah, Thirlmere Lakes National Park. *Ian Brown (NSW National Parks and Wildlife Service)*

8.14.5 Gaps in knowledge and future directions

- There are few studies examining the effects of fire on vegetation in the Greater Blue Mountains in the face of climate change. The long-term conservation of vegetation types will depend on a greater understanding of fire behaviour under a range of climate change scenarios. The Biodiversity Conservation Science Section in the NSW Department of Environment and Climate Change is undertaking a three-year study to examine the relationship between fire history, climate change and potential impacts on plant communities in the Greater Blue Mountains (Hammill & Bradstock 2006).
- The adaptive threshold responses of many plant and animal species to changes in vegetation cover following environmental disturbance (e.g. more intense and/or more frequent fires, changes in seasonal rainfall and temperature) is unknown and requires further investigation.
- The germination and early growth requirements of many species are unknown and require investigation. There is a need to look not only at responses to changes in vegetation cover, but also to changes in vegetation structure and the species composition of ecosystems. The lack of knowledge of the ecology of the approximately 1,500 plant species and the many thousands of animal species of the area is a critical deficiency.
- The impact of reduced runoff and environmental flows on fauna and flora require further investigation.
- Moist area refugia are likely to be important in the future. Research to establish what might be lost or benefit from conservation measures, to identify key wet areas, and to establish their role in future management, is essential.
- Ecologically sensitive areas need to be defined and mapped. These include threatened ecological communities such as the Newnes Plateau Shrub Swamps, regionally significant communities such as monkey gum (*Eucalyptus cypellocarpa*), Sydney peppermint (*E. piperita*) and tall open forest, as well as the habitats of rare and threatened plants and animals.

8.15 Purnululu National Park

Aerial shot of domes. *Rod Hartvigsen and the Department of the Environment, Water, Heritage and the Arts*

8.15.1 Climate change scenarios for north-west Australia

The following climate change projections for north-west Australia [63] are based on a 'high' greenhouse gas emissions scenario.[64]

- The north-west region of Australia is likely to experience warmer temperatures (+1.3 °C ± 0.6 °C) by 2030, with hotter days and fewer cold nights.
- CSIRO climate change scenarios indicate that annual average rainfall is likely to fall by 3.5% ± 11% by 2030. There is an increased likelihood of extreme weather events and flash flooding.
- There is likely to be a decrease in water runoff into rivers resulting from a higher evaporative demand (3.7% ± 2.5%) and a small decrease in annual rainfall.

8.15.2 Summary of impacts

Purnululu National Park is located at about 17°15'–17°46'S and 128°15'–128°55'E in the East Kimberley region of Western Australia—the 'wet-dry tropics'. It covers an area of almost 240,000 ha. The property features habitats ranging from riverine ecosystems to spinifex-dominated communities. The Bungle Bungle Range, composed of outstanding geomorphic sandstone towers marked by horizontal bands of cyanobacteria [65] crusts along the karst cliffs, is the preeminent feature of the park. Purnululu National Park is managed under the *Conservation and Land Management Act 1984* by Western Australia's Department of Environment and Conservation (DEC). A change in management arrangements provides for joint management of the area by traditional owners and DEC, directed by the Purnululu Park Council. The site was added

63 Purnululu falls outside but close to the north-west Australian region used by CSIRO in modelling climate change scenarios. Purnululu is in the transition zone between the monsoon savannah and the arid desert of central Australia and climate may vary between the characteristics of these two regions.

64 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

65 Single-celled photosynthetic microorganisms.

to the World Heritage List on the basis of two broad 'natural heritage' criteria—geological and aesthetic. The impacts of climate change will vary depending on the vulnerability of particular ecosystems and their geographical location within the property. While the area also features natural and cultural values including rock art, grinding marks, archaeological artifacts, and continuing links of spiritual and economic importance for the area's traditional inhabitants, these have not yet been recognised as World Heritage values for inscription of the property and therefore are not considered in this assessment.

8.15.3 Potential climate change impacts on World Heritage values

Impact on natural values

Natural criteria

Criterion (vii): To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Criterion (viii): To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.

Values include:

Twenty million year record of geomorphic processes and landscape evolution associated with the formation of mature karst in siliceous sedimentary rocks; extensive areas of cone karst formation, and exceptional development of cyanobacterial banding and biological surface crusts in the exposed sedimentary layers.

As an outstanding example of karst landscapes, the Bungle Bungle Range within Purnululu National Park illustrates the interaction of geological, biological, erosional and climatic phenomena over a long period. Purnululu National Park also exemplifies evidence of the geomorphic processes of dissolution, weathering and erosion in an ancient sedimentary landscape under a savanna climatic regime. Evidence of these phenomena includes the presence of cyanobacterial surface crusts and bands in cliff faces, which are important in maintaining the stability of the landforms.

There has been no comprehensive study of the potential impacts of climate change on the property as a whole, or in the north-west Australian region. The World Heritage values centre on the property's significance as a landform that is both picturesque and of scientific interest. As noted elsewhere in this document, geomorphological changes are a natural process, and one reason for the importance of properties such as Purnululu National Park and Willandra Lakes Region is that they provide evidence of climate change impacts on the landscape over millions of years (Sharples 2002; Swart 1994). Overall, it is unclear whether climate change will significantly affect these 'landform' values through, for example, substantially accelerated erosion of karst cones or fundamental damage to cliff-face bands created by cyanobacteria.

The absence of comprehensive research regarding the potential impacts of climate change on Purnululu National Park's landforms inhibits an authoritative assessment. Research in this area would be appropriate, and might include an examination of the vulnerability of cyanobacterial banding, given the uncertainty about particular threats such as acidification of surface/rain water, and about the characteristics of some crusts and bands. Cyanobacteria are not uniform; some species such as *Tolypothrix* and *Chroococcidiopsis* are more drought-tolerant than others and less affected by temperature changes (Potts 1999; Wynn-Williams et al. 2000).

The impact of likely global climate change on Purnululu National Park's geomorphology in the near to mid-term is unlikely to be pronounced or feasibly addressed on a large scale through remedial action that is specific to the property. Elsewhere in this document, attention has been drawn to discussion of landscape maintenance, with some acceptance among specialists that geological change is an ongoing process that should be viewed on a geological timescale rather than in terms of a few years or a few decades (Sharples 2002). That conceptualisation has been reflected in arguments that concern for particular landforms (in contrast to accelerated weathering or loss of human-constructed sculptures, buildings and urban precincts such as Venice) are misplaced, or are likely to absorb resources more appropriately allocated elsewhere.

Dramatically sculptured arrays of sandstone cones, extraordinary beauty and majestic scale of the horizontal banding provided by the cyanobacterial crusts against the orange sandstone, and diversity of landforms and ecosystems providing a sympathetic visual buffer (with spinifex grassland, closed forests of northern monsoonal taxa in the moister gorges, paperbark–red gum forests of the riparian zone, and the wide grasslands and open woodland of the plains).

As with Shark Bay, it appears unlikely that climate change in the immediate term will fundamentally erode the aesthetic attributes of Purnululu National Park. It may, however, negatively impact on both biological diversity and cultural values, changes to which are unlikely to make much difference to the key aesthetic values. It is noted that biological and cultural values were identified in Australia's World Heritage nomination for the property, but have not yet been accepted as of World Heritage value by the World Heritage Committee.

Particular pressure will be placed on endangered species within the region, such as the pale field rat (*Rattus tunneyi*) and the large-footed bat (*Myotis adversus*) (Baillie et al. 2004; Braithwaite & Griffiths 1996). Increased temperatures and extended droughts will affect amphibian species, such as frogs, with habitats in gorges and rainforest niches, both directly and through crowding by competitors (Hines et al. 1999; Williams & Hero 2001). Changes to the intensity of storms, and thus floods, may affect ecosystem compositions on the fringe of the savanna area (Capon 2002; Kingston 2005; Pickup 1991). Much of the property is dominated by spinifex species (genus *Triodia*), which are likely to increase in geographical spread if the eastern sector of Purnululu National Park becomes more arid (Woinarski 1992).

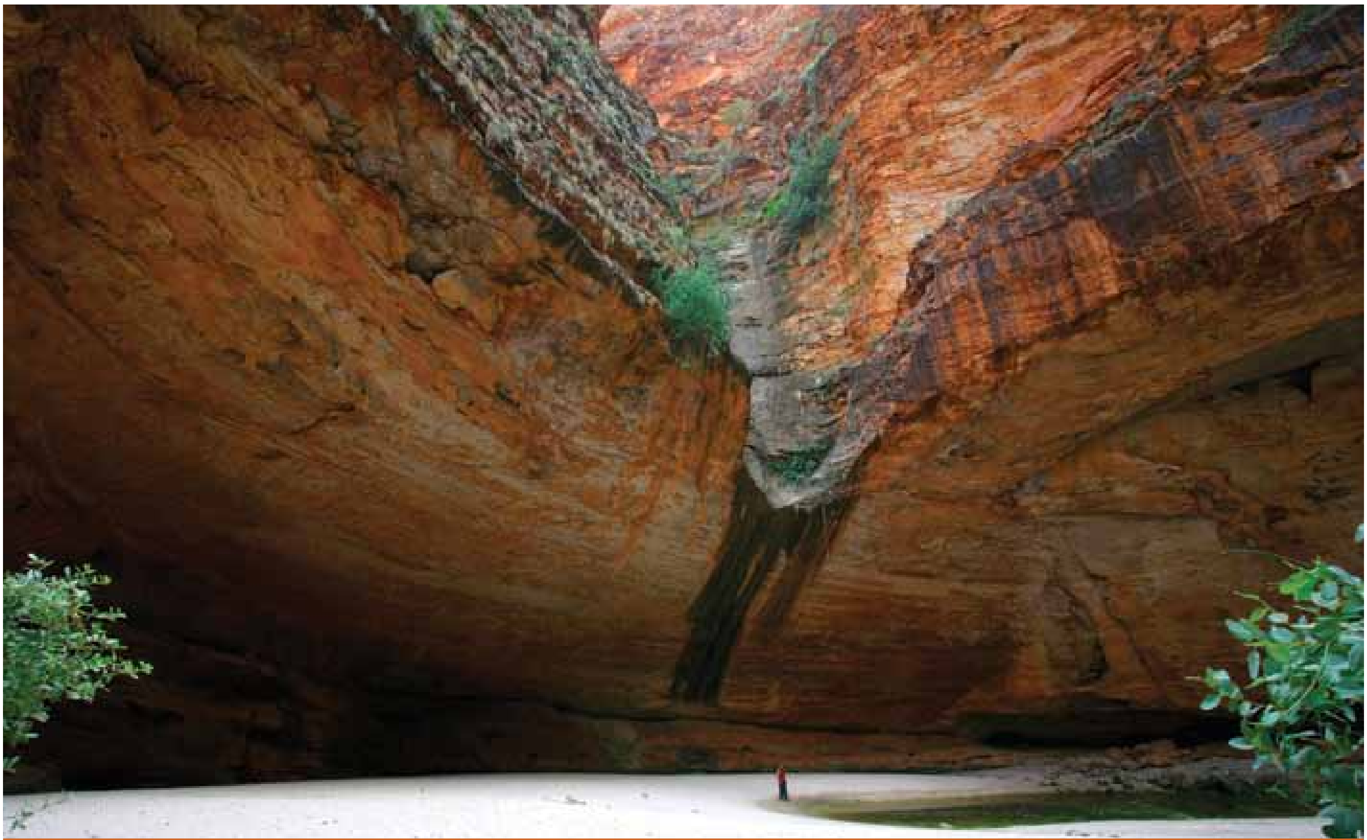
Spinifex species found in Purnululu National Park:

- *Triodia bitextura*
- *Triodia microstachya*
- *Triodia bynoei*
- *Triodia procera*
- *Triodia bunglensis*
- *Triodia pungens*
- *Triodia burbidgeana*
- *Triodia spicata*
- *Triodia epactia*
- *Triodia stenostachya*
- *Triodia intermedia*
- *Triodia wiseana*
- *Triodia inutilis*

Expansion of spinifex poses challenges to fire management, with traditional regimes being of importance to avifauna, small mammals and insect species adversely affected by major fire events in rangelands (Allan & Southgate 2001; Masters 1993). The extent of vulnerabilities within Purnululu National Park would be worthy of identification and assessment.

8.15.4 Associated threats

The property contains numerous ecosystems, some of which are potentially threatened by climate change (e.g. heightened exposure to recurrent wildfires in the spinifex plains to the east in the absence of traditional fire management regimes) and by developments in neighbouring regions. For example, migration of pests, such as the cane toad, would have a fundamental negative effect on sensitive fauna in the wetter parts of the property (Allan & Southgate 2001; Borrini-Feyerabend et al. 2004; Bowman 1998; Edwards et al. 2004; Sharp & Bowman 2004).



Echidna Chasm walk. *Rod Hartvigsen and the Department of the Environment, Water, Heritage and the Arts*

8.15.5 Gaps in knowledge and future directions

- The remoteness of the region and difficulties in access because of its topography mean that there are gaps in identification of individual species and knowledge of species interactions. That is evident in ongoing description of new taxa (Barrow et al. 2006; Pfeil & Craven 2002), and uncertainties about the viability and interaction of regional biological reserves (Burbidge & McKenzie 1989; Woinarski 1992). More broadly, the literature review suggests that there is a perceptible 'silo effect'—that is, there is little emphasis placed on cross-fertilisation of knowledge and ideas or knowledge sharing across properties, conceivably resulting in lost opportunities to draw conclusions from the study of habitats elsewhere in Australia (including across the border in the Northern Territory and in parts of Queensland).
- There are challenges in terms of fire management, with traditional regimes recognised as important to maintain biodiversity values affected by major fire events in rangelands (Allan & Southgate 2001; Masters 1993). The extent of vulnerabilities within Purnululu National Park is worthy of identification and assessment.
- There is some uncertainty about the impact of particular aspects of climate change on cyanobacterial species and crust formation.

8.16 Royal Exhibition Building and Carlton Gardens

Exterior of the Royal Exhibition Building. *Michelle McAulay and the Department of the Environment, Water, Heritage and the Arts*

8.16.1 Climate change scenarios for Victoria

The following climate change scenarios for Victoria are based on a 'high' greenhouse gas emissions scenario.[66]

- There is an increased likelihood of higher temperatures (1.1 °C ± 0.4 °C) and extreme weather events through climate change.
- Average annual rainfall is projected to decline (-3.5% ± 11%), although some seasons will be drier than others and some rain may fall in more extreme events.
- There is likely to be an increase in evaporative demand, and less runoff into rivers and streams.
- Droughts are likely to become more frequent and more severe.
- Sea levels are expected to rise by as much as 17 cm.[67]

8.16.2 Summary of impacts

The Royal Exhibition Building and Carlton Gardens (37°48'S, 144°58'E) occupy an elevated position on the edge of the central business district in Melbourne, Victoria, and cover an area of 26 ha. The site is jointly managed by Museum Victoria and the City of Melbourne. The most discernable impact to date is the drought-affected mature trees in the Carlton Gardens, although that appears to be less significant than other urban locations in Melbourne such as the Royal Botanic Gardens. Potential rises in sea levels do not pose direct concerns for the site. It is likely to be the least affected of the World Heritage properties by climate change, consistent with its location and characteristics.

66 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

67 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

Impacts on the Royal Exhibition Building likely to occur from global warming include:

- temperature impacts (solar radiation affects building fabric and can accelerate deterioration; and changes in humidity levels can affect historic collections, decorations and building fabric)
- impacts from changes in levels of rain (including impacts from less and more rain), which can affect garden vegetation, building fabric and soil chemistry
- soil chemistry and water content impacts (changes in salinity cause salt damage in buildings and relics, and may impact on salt-intolerant species in the gardens; high clay content soils in drought result in potentially serious cracking and may also affect garden vegetation)
- biological and pest issues resulting from changing temperature and rainfall levels
- inclement weather including wind, severe rain, lightning and hail which can all directly affect building fabric and gardens.

There is currently a lack of data available about potential impacts of climate change on built heritage.

8.16.3 Potential climate change impacts on World Heritage values

Cultural criterion

Criterion (ii): To exhibit an important interchange of human values over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design.

The site comprises the Royal Exhibition Building and Carlton Gardens, laid out by the building's architect (Joseph Reed) in 1880, and are substantially intact (Dunstan 1996). The site is bounded on four sides by streets and urban development. It is also occupied by Melbourne Museum, an arm of Museum Victoria (the state government museum agency), a children's playground and low-intensity sports facilities.

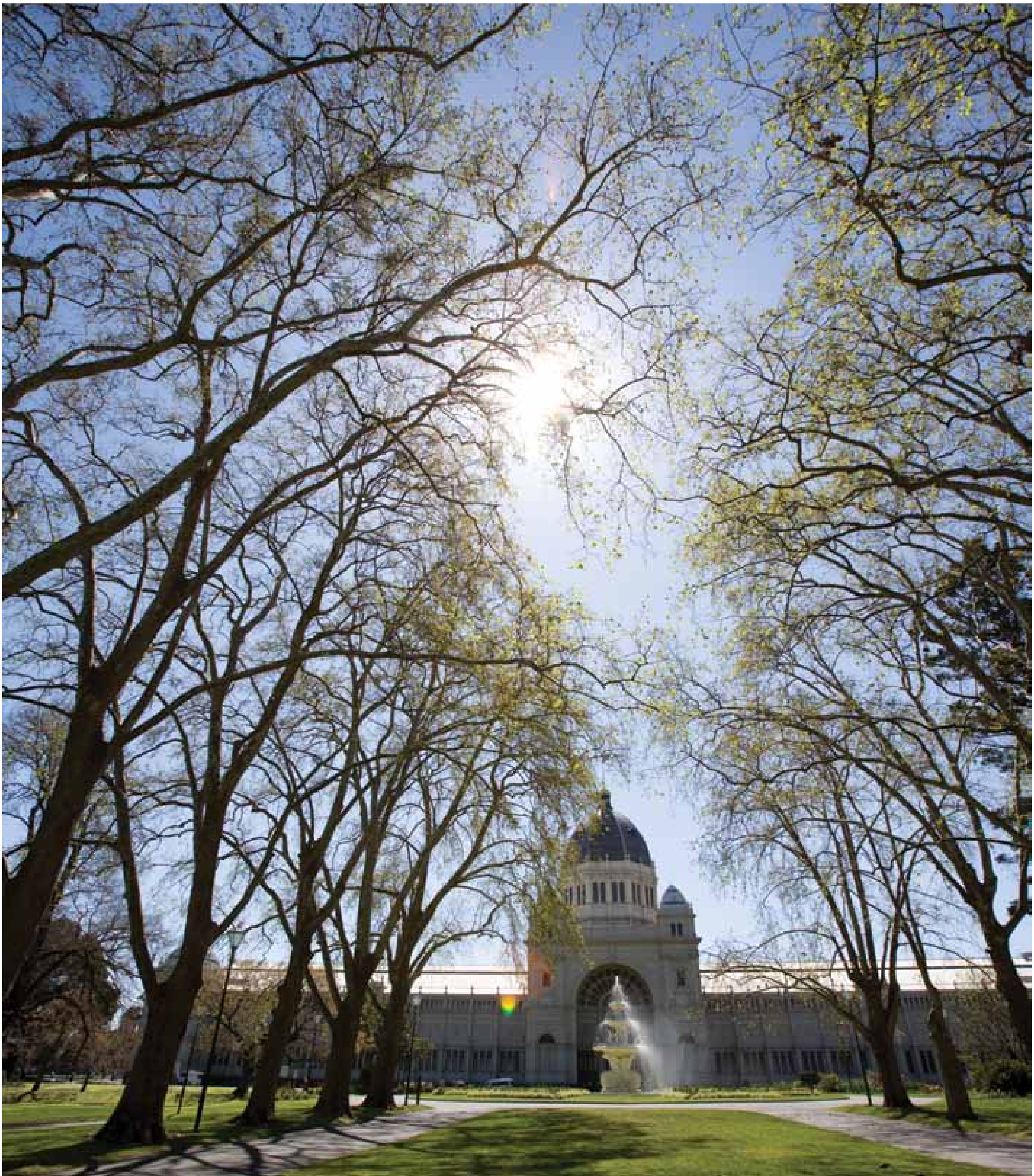
The building and gardens have been assessed to have '*outstanding universal value as a rare surviving manifestation of the international exhibition phenomenon of the late nineteenth and early twentieth centuries*'. They have significance as being the venue for the opening of the first Commonwealth Parliament and as an example of 'boom period' architecture. They remain in active use, with the gardens, for example, hosting a large-scale horticultural event each year (with associated site remediation) and the building serving as a venue for trade shows and other events.

The Royal Exhibition Building is the surviving component of a complex of structures erected for the 1880 Melbourne Great International Exhibition. It is constructed of brick, timber, slate and steel. There are no fundamental concerns about its structural soundness, for example, through subsidence or weathering of particular features. It features a number of murals. It has been modified since initial construction, with removal of some additions and restoration after damage through fire and use (Dunstan 1996). Restoration has been undertaken in accordance with the principles of the Australia ICOMOS Burra Charter (1999).

Carlton Gardens feature mature native and exotic flora (e.g. oaks, elms and decorative shrubbery), extensive lawns in the English park style, parterre flowerbeds, fountains and two small ponds.

The property does not formally feature indigenous fauna; the Melbourne City Council has taken steps to address concerns about possum damage to trees in the gardens. The council is also recovering early plantings, along with removal of unsympathetic fixtures that date from after the 1880s. The gardens include water reticulation and drainage appropriate to a major destination for tourists and residents/workers in the precinct.

Concerns regarding the potential impact of climate change are less significant, in terms of the shape and severity of threats, than for the other World Heritage properties discussed in this document.



Exterior of the Royal Exhibition Building showing some of the fine gardens. *Michelle McAulay and the Department of the Environment, Water, Heritage and the Arts*

Relatively lower concerns reflect:

- the nature of the specific World Heritage value (essentially maintenance of a well-preserved Victorian building and its gardens)
- that climate change per se is unlikely to pose a fundamental threat to the building. Professional evaluation of potential impacts of climate change is carried out on behalf of Heritage Victoria.

Management challenges are unlikely to be significantly exacerbated by climate change. There are no indications that warming will significantly change visitation to the property. However, due to the impact of drought, it is likely to become increasingly difficult to maintain plantings of species that would have historically appeared in the gardens; to some extent this has already been accommodated in that restoration of the building and gardens has featured an emphasis on 'water wise' management of flora and investment in enhanced fire protection systems for the building. Increased CO_2 levels would not appear to pose fundamental problems for vegetation in the gardens. Climatic change may pose a challenge for maintaining the fabric of the building; for example, from pest infestation of wooden components, or deterioration of fittings and murals as a result of changing soil moisture levels. Furthermore, an increase in extreme weather events (severe hailstorms and strong winds) could cause damage to the building's structure (e.g. roofing or water damage and localised flooding).

8.16.4 Gaps in knowledge and future directions

In the context of climate change, the following issues need to be addressed to ensure the future conservation of the Royal Exhibition Building and Carlton Gardens and its values:

- Given that decisions on management of the building and gardens involve Melbourne City Council officials, Museum Victoria, other elements of the Victorian Government and commercial contractors, improved sharing of information about the identification and evaluation of potential impacts is desirable. Some decision-makers may be unaware of potential climate change impacts on the building and gardens; others will disagree about priorities relative to other locations.
- Independent and qualified assessment of potential impacts is also desirable.

Interior of the Royal Exhibition Building. *Michelle McAulay & the Department of the Environment, Water, Heritage and the Arts*

8.17 Sydney Opera House

The Sydney Opera House with the Sydney Harbour Bridge in the background. *Dragi Markovic and the Department of the Environment, Water, Heritage and the Arts*

8.17.1 Climate change scenarios for New South Wales

The following climate change scenarios for New South Wales, relative to 1990, are based on a 'high' greenhouse gas emissions scenario.[68]

- Average annual temperature is expected to rise 1.3 °C ± 0.6 °C by 2030, with an increase in the number of hot days.
- Annual average rainfall is unlikely to change, but seasonality may change, with less rain expected in the winter and spring and a little more in summer and autumn.
- Higher evaporative demand is likely to reduce runoff into streams and rivers.
- Extreme weather events are likely to result in increase in storm intensity and flash flooding or hailstorms.
- Droughts, and the number of days of extreme fire danger, are likely to increase in frequency, increasing the risk of severe fire events (Hennessy et al. 2006).
- Sea level is expected to rise by about 17 cm by 2030.[69]

8.17.2 Potential climate change impacts on World Heritage values

Cultural criterion

Criterion (i): To represent a masterpiece of human creative genius.

Sydney Opera House is a great architectural work of the 20th century. It represents multiple strands of creativity, both in architectural form and structural design, a great urban sculpture carefully set in a remarkable waterscape and a world-famous iconic building.

68 Derived from CSIRO, 2006 projections for Australia; 'high emissions' scenario based on the IPCC A1FI scenario. Note observed climate trends for CO_2, temperature and sea level rise are currently exceeding the IPCC 'high emissions' scenarios (Rahmstorf et al. 2007).

69 Based on a 'high' IPCC scenario; global sea level rise projections based only on thermal expansion (no ice sheet contribution taken into account) so are likely to be conservative.

Close up of sails. *Mark Mohell and the Department of the Environment, Water, Heritage and the Arts*

Set on the banks of Sydney Harbour, Sydney Opera House is a recognised masterpiece of late modern architecture value. Its value lies in the vision of the architect of the building, Jørn Utzon, that pushed architecture and engineering to new limits, and which has had an enduring influence on late 20th century architecture and beyond.

Concerns regarding the potential impact of climate change on Sydney Opera House are presently less significant, in terms of the shape and severity of threats, than for the other World Heritage properties discussed in this document.

Sydney Opera House would appear to be at risk from projected sea level rise, as the forecourt of the building is only 3.5 m above sea level. The building structure is supported by 580 piers sunk 25 m below sea level. Sea level rise can have several types of impacts. The rising salt associated with slowly increasing sea level rise may have implications for the building fabric. Storm surges—especially where associated with high tides—on top of increased sea level, can cause significant coastal damage and has potential to affect the building.

Higher temperatures and changes in humidity—as well as extreme weather events including wind, severe rain, lightning and hail—can have a direct impact on the fabric of buildings. Changes in rainfall (prolonged drought or excessive rainfall) can also affect building fabric and soil chemistry (UNESCO 2006). Potential exists for increase in pest and biological infestations, although this is less likely to impact on concrete and glass constructions such as the Opera House.

8.17.3 Gaps in knowledge and future directions

Sydney Opera House is to develop a Heritage Risk Management Plan stemming from its endorsed conservation management plan, but it is not known if this will specifically address sea level rise risks (Pearson 2007).

The effect of sea level rise on the building's structure and fabric is worthy of assessment.

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10. APPENDICES

Appendix A: Climate changes projected for Australia

1. Temperature

The CSIRO Atmospheric Research Division has used a number of global climate models (GCM) to investigate future climate change scenarios for Australia (CSIRO 2006). Relative to 1990 temperatures, these scenarios indicate a warming trend across the continent by as much as 2 °C by 2030 and 7 °C by 2070. According to these climate models, some World Heritage properties may experience higher temperature increases than others. Generally, World Heritage properties further inland (e.g. Uluṟu-Kata Tjuṯa, Willandra Lakes Region, Purnululu National Park) may experience higher temperature increases than those near the coast (e.g. Kakadu National Park, Tasmanian Wilderness). Unfortunately, the coarse grid scale of these GCMs does not provide fine-scale changes at the localised region for some of the World Heritage properties.

2. Rainfall

Precipitation scenarios for Australia vary seasonally and annually across the continent. The projected annual average ranges for much of Australia are -10% to +10% by 2030. Rainfall scenarios based on CSIRO 2006 climate estimates are summarised in Table 15.

Table 14. ***Average annual rainfall for 2030 relative to 1990 for Australia's World Heritage properties*** **(adapted from: CSIRO 2006). Note: does not include all World Heritage properties, e.g. Lord Howe Island, Macquarie Island, Heard and McDonald Islands, and Shark Bay.**

Continental/Oceanic regions	Average annual rainfall (low [70] greenhouse gas emissions scenario) ± uncertainty	Annual average rainfall (high [71] greenhouse gas emissions scenario) ± uncertainty	World Heritage property
Top End	0% ± 3%	0% ± 7.5%	Kakadu National Park
Central Australia	0% ± 6.5%	0% ± 15%	Uluṟu-Kata Tjuṯa National Park
North Western Australia	-1.5% ± 5%	-3.5 ± 11%	Purnululu National Park (location very close to the modelled NW Australia area)
North Eastern Queensland	-1.5 ± 5%	-3.5 ± 11%	Wet Tropics of Queensland; Great Barrier Reef; Riversleigh Fossil Mammal Sites
South Eastern Queensland	-1.5% ± 5%	-3.5% ± 11%	Fraser Island; Gondwana Rainforests of Australia
New South Wales	0% ± 6.5%	0% ± 15%	Greater Blue Mountains Area; Gondwana Rainforests of Australia; Sydney Opera House

70 Low global warming scenario: see CSIRO (2006) for an explanation.

71 High global warming scenario: see CSIRO (2006) for an explanation.

Continental/Oceanic regions	Average annual rainfall (low [70] greenhouse gas emissions scenario) ± uncertainty	Annual average rainfall (high [71] greenhouse gas emissions scenario) ± uncertainty	World Heritage property
Southern South Australia	-3% ± 3%	-7.5% ± 7.5%	Naracoorte Fossil Mammal Site
Victoria	-1.5% ± 5%	-3.5 ± 11%	Royal Exhibition Building and Carlton Gardens; Willandra Lakes Region (NSW, but falls within the annual average rainfall projection range for Victoria)
Tasmania	+1.5% ± 5%	+3.5% ± 11%	Tasmanian Wilderness
South Western Australia	-5% ± 5%	-11% ± 11%	(Shark Bay is to the north of the modelled area)

3. Tropical cyclones and extreme weather events

Tropical cyclones are likely to become more intense with higher wind speeds (5–10% increase) (CSIRO 2006) and for stronger cyclones to occur further south along the Queensland coast. Research has shown an increase in the destructiveness of cyclones since the 1970s, which correlates with the observed increase in sea surface temperature (Emanuel 2005). Extreme rainfall and storm events are likely to become more frequent for most regions.

4. Evaporation and moisture balance

Increased evaporative demand associated with higher temperatures (CSIRO 2006) is likely to lead to an increase in severity of drought for most of Australia's World Heritage properties. Evaporation and moisture budgets have suggested an annual reduction in soil moisture content in the range of 40–130 mm by 2030 (Pittock 2003). Runoff into streams and rivers is likely to be reduced in most regions as a consequence. Changes in rainfall have magnified impacts on runoff. Modelling suggests that runoff by the year 2030 could change by -5 to +15% for the north-east coastal region of Australia, while in some other regions such as Tasmania (i.e. Tasmanian Wilderness) streamflow response is likely to be unpredictable (Chiew & McMahon 2002). Higher evaporative demand and higher temperatures are likely to result in an increase in the threat of extreme wildfires.

5. Sea level rise

From 1993 to 2003, global mean sea level has been rising at a rate of around 3 mm/yr (Bindoff et al. 2007). Thermal expansion of the oceans and widespread melting of land ice will result in further global sea level rise. Based on the relative sea level rise around Australia (1.2 mm/year) (Church et al. 2004), the average sea level rise by 2030 could be as high as 3 cm under a low greenhouse gas emissions scenario or 17 cm under a high greenhouse gas emissions scenario (CSIRO 2006). However, even a moderate rise would be undesirable for some of Australia's World Heritage properties such as Kakadu National Park and Shark Bay. Certain landforms (e.g. 'soft' shorelines) including muddy estuarine and deltaic shorelines are particularly vulnerable to rising sea levels and severe storm-surge events (Sharples 2006).

Table 15. Summary of climate change scenarios by 2030 (as an estimate of change) for each World Heritage region derived from CSIRO climate modelling for Australia relative to 1990 (Source: CSIRO 2006). Figures are based on a 'high' greenhouse gas emissions scenario (the A1FI scenario (IPCC 2000)).

World Heritage property	Temperature °C ± uncertainty	Sea level	Rainfall ± uncertainty					Evaporation ± uncertainty	No. of high to extreme forest fire danger days	Tropical cyclones
	Annual average	Average	Annual average	Summer	Autumn	Winter	Spring	Average annual potential	Annual average	
Kakadu National Park	+1.3 °C ± 0.6 °C	+17 cm	0% ± 7.5%	-3.5% ± 11%	0% ± 15%	n.a.	+3.5% ± 18.5%	+3.7% ± 3.7%	n.d.	+10%
Great Barrier Reef	+1.3 °C ± 0.6 °C	+17 cm	-3.5% ± 11%	+3.5% ± 11%	-7.5% ± 15%	n.d.	0% ± 22.5%	+3.7% ± 3.7%	n.a.	+10%
Willandra Lakes Region	+1.1 °C ± 0.4 °C		-3.5% ± 11%	0% ± 15%	-3.5% ± 11%	-3.5% ± 11%	-11% ± 11%	+5% ± 2.5%	+11 days	
Lord Howe Island Group	+1.3 °C ± 0.6 °C	+17 cm	0% ± 15%	+3.5% ± 18.5%	+3.5% ± 18.5%	-7.5% ± 15%	-7.5% ± 15%	+5.6% ± 4.4%	+10 days	
Tasmanian Wilderness	+1.1 °C ± 0.4 °C	+17 cm	+3.5% ± 11%	-7.5% ± 15%	0% ± 15%	+3.5% ± 11%	-3.5% ± 11%	+4.4% ± 1.9%	+0.5 day	
Gondwana Rainforests of Australia	(upper) +1.3 °C ± 0.6 °C	+17 cm	-3.5% ± 11%	0%±15%	-7.5% ± 15%	-7.5% ± 15%	-7.5% ± 15%	+5.6% ± 4.4%	n.a.	
	(lower) +1.3 °C ± 0.6 °C	+17 cm	0% ± 15%	+3.5% ± 18.5%	+3.5% ± 18.5%	-7.5% ± 15%	-7.5% ± 15%	+5.6% ± 4.4%	+10 days	
Uluru-Kata Tjuta National Park	+1.7 °C ± 0.6 °C		0% ± 15%	0% ± 15%	0% ± 15%	n.a.	n.a.	+5.6% ± 3.1%	n.d.	
Wet Tropics of Queensland	+1.3 °C ± 0.6 °C	+17 cm	-3.5% ± 11%	+3.5% ± 11%	-7.5% ± 15%	n.d.	0% ± 22.5%	+3.7% ± 3.7%		+10%
Shark Bay, Western Australia	+1.1 °C ± 0.7 °C	+17 cm	-11% ± 11%	-7.5% ± 15%	-7.5% ± 15%	-11% ± 11%	-11% ± 11%	+4.3% ± 3.1%	n.d.	

World Heritage property	Temperature °C ± uncertainty	Sea level	Rainfall ± uncertainty					Evaporation ± uncertainty	No. of high to extreme forest fire danger days	Tropical cyclones
	Annual average	Average	Annual average	Summer	Autumn	Winter	Spring	Average annual potential	Annual average	
Fraser Island	+1.3 °C ± 0.6 °C	+17 cm	-3.5% ± 11%	0% ± 15%	-7.5% ± 15%	-7.5% ± 15%	-7.5% ± 15%	+5.6% ± 4.4%	n.a.	
Australian Fossil Mammal Sites (Riversleigh and Naracoorte)	+1.3 °C ± 0.6 °C (Riversleigh)		-3.5% ± 11%	+3.5% ± 11%	-7.5% ± 15%	n.d.	0% ± 22.5%	+3.7% ± 3.7%	n.d.	+10%
	+0.9 °C ± 0.6 °C (Naracoorte)		-7.5% ± 7.5%	-7.5% ± 15%	-3.5% ± 11%	-11% ± 11%	-11% ± 11%	+3.7% ± 2.5%	n.a.	
Heard and McDonald Islands	n.d.	+17 cm	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	
Macquarie Island	+1.1 °C ± 0.4 °C	+17 cm	+3.5% ± 11%	-7.5% ± 15%	0% ± 15%	+3.5% ± 11%	-3.5% ± 11%	+4.4% ± 1.9%	n.a.	
Greater Blue Mountains Area	+1.3 °C ± 0.6 °C	+17 cm	0% ± 15%	+3.5% ± 18.5%	+3.5% ± 18.5%	-7.5% ± 15%	-7.5% ± 15%	+5.6% ± 4.4%	+10 days	
Purnululu National Park	+1.3 °C ± 0.6 °C		-3.5% ± 11%	-3.5% ± 11%	0% ± 15%	n.a.	n.a.	+3.7% ± 2.5%	n.d.	
Royal Exhibition Building and Carlton Gardens	+1.1 °C ± 0.4 °C	+17 cm	-3.5% ± 11%	0% ± 15%	-3.5% ± 11%	-3.5% ± 11%	-11% ± 11%	+5% ± 2.5%	+11 days	
Sydney Opera House	+1.3 °C ± 0.6 °C	+17 cm	0% ± 15%	+3.5% ± 18.5%	+3.5% ± 18.5%	-7.5% ± 15%	-7.5% ± 15%	+5.6% ± 4.4%	+10 days	

n.d. = No data available

n.a. = Not applicable

Appendix B: An eight-step approach to guide vulnerability assessments [72]

1. Define study area together with stakeholders and choose spatial and temporal scale.
2. Get to know place over time by reviewing literature, contacting and collaborating with researchers, spending time in the field with stakeholders and assessing nearby areas.
3. Hypothesise who is vulnerable to what: refine focus on stakeholder subgroups, and identify driving stresses and interactions of stresses.
4. Develop a causal model of vulnerability: • Examine exposure, sensitivity and adaptive capacity. • Formalise into model(s).
5. Find indicators for the elements of vulnerability: • Exposure indicators. • Sensitivity indicators. • Adaptive capacity indicators.
6. Operationalise model(s) of present vulnerability: • Apply model(s) to weigh and combine indicators. • Apply model(s) to produce a measure of present vulnerability. • Validate results with stakeholders, etc.
7. Project future vulnerability: • Choose scenarios with stakeholders. • Scenarios should demonstrate full range of likely trends. • Apply model(s) to produce a measure of future vulnerability.
8. Communicate vulnerability creatively: • Use multiple interactive media. • Be clear about uncertainty. • Trust stakeholders.
9. Project future vulnerability: • Choose scenarios with stakeholders. • Scenarios should demonstrate full range of likely trends. • Apply model(s) to produce a measure of future vulnerability.
10. Communicate vulnerability creatively: • Use multiple interactive media. • Be clear about uncertainty. • Trust stakeholders.

For a detailed discussion see: Schröter et al. (2005) Assessing vulnerabilities to the effects of global change: an eight step approach, *Mitigation and Adaptation Strategies for Global Change*, 10: 573–596. According to these authors, for vulnerability assessments the role of numerical modelling is the projection of future states of a system. Here, steps 1–3 take place prior to modelling, whereas steps 4–8 take place as part of the modelling and model refinement process. Source: UNESCO (2006).

72 See Chapter 5.

Appendix C: Summary of likely climate change threats and assessment of adaptive capacity of Australia's World Heritage properties

World Heritage criteria	World Heritage properties	Examples of property features reflecting World Heritage values	Major threats from climate change	Adaptive capacity
Natural: • (ix) To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals. • (x) To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.	• Kakadu National Park • Great Barrier Reef • Lord Howe Island Group • Tasmanian Wilderness • Gondwana Rainforests of Australia • Wet Tropics of Queensland • Shark Bay, Western Australia • Fraser Island • Australian Fossil Mammal Sites • Heard and McDonald Islands • Greater Blue Mountains Area	Terrestrial: • Open forest and woodlands • Rainforest communities • Invertebrates • The diversity of plant and animal species • Relict species with Gondwanan affinities • Examples of stromatolite and microbial mats	• Changes in annual and seasonal rainfall • More intense storms and cyclones • Increase in temperature • Changed fire regimes (more frequent and intense) • More frequent severe droughts, affecting conditions on land • Reduced runoff into streams and creeks • Increased carbon dioxide (CO_2)	Low
	• Great Barrier Reef • Lord Howe Island Group • Tasmanian Wilderness • Shark Bay, Western Australia • Fraser Island	Marine: • Coral reefs • Diversity of marine benthic algae • Examples of stromatolite and microbial mats • Diversity of marine fish species and other marine species—reptiles and mammals	• Sea level rise • Ocean acidification • Storm surges • Increase in sea surface temperatures	

World Heritage criteria	World Heritage properties	Examples of property features reflecting World Heritage values	Major threats from climate change	Adaptive capacity
Natural: • (vii) To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance. • (viii) To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.	• Kakadu National Park • Great Barrier Reef • Willandra Lakes Region • Lord Howe Island Group • Tasmanian Wilderness • Gondwana Rainforests of Australia • Uluru-Kata Tjuta National Park • Wet Tropics of Queensland • Shark Bay, Western Australia • Fraser Island • Australian Fossil Mammal Sites • Heard and McDonald Islands • Macquarie Island • Purnululu National Park	• Coastal dunes • Plateau tops, ridges, exposed rocks, cliffs, rocky slopes • Archaeological sites • Freshwater dune lakes • Subtropical patterned fens • Cone karst formations • Fossil sites	• Changed fire regimes • Acidic rainfall • More intense storms and cyclones • Increased erosion • Increase in temperature	Moderate

World Heritage criteria	World Heritage properties	Examples of property features reflecting World Heritage values	Major threats from climate change	Adaptive capacity
Cultural: • (iii) To bear a unique or at least exceptional testimony to a civilization which is living or which has disappeared. • (iv) To be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history. • (v) To be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change. • (vi) To be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance.	• Kakadu National Park • Willandra Lakes Region • Tasmanian Wilderness • Uluru-Kata Tjuta National Park	• Human settlement and land use • Archaeological sites	• Changed fire regimes • Increased erosion • Increase in temperature and changes in humidity	Moderate
Cultural: • (ii) To exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design.	• Royal Exhibition Building and Carlton Gardens	• Built environment	• Increase in temperature • Drought • Acid rainfall • Increase in storm frequency	High
Cultural: • (i) To represent a masterpiece of human creative genius.	• Kakadu National Park • Sydney Opera House	• Aboriginal rock art • Built environment	• Acid rainfall • Fire • Increase in storm intensity	Moderate to High

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