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Australia and New Zealand

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CONTENTS

EXECUTIVE SUMMARY

The Australia and New Zealand Region: This region spans the tropics to mid-latitudes and has varied climates and ecosystems, including deserts, rainforests, coral reefs, and alpine areas. The climate is strongly influenced by the surrounding oceans. The El Niño-Southern Oscillation (ENSO) phenomenon leads to floods and prolonged droughts, especially in eastern Australia and parts of New Zealand. The region therefore is sensitive to the possible changes toward a more El Niño-like mean state suggested by Working Group I. Extreme events are a major source of current climate impacts, and changes in extreme events are expected to dominate impacts of climate change. Return periods for heavy rains, floods, and storm surges of a given magnitude at particular locations would be modified by possible increases in intensity of tropical cyclones, mid-latitude storms, and heavy rain events (medium confidence) and changes in the location-specific frequency of tropical cyclones (low to medium confidence). Scenarios of climate change based on recent coupled atmosphere-ocean climate models suggest that large areas of mainland Australia will experience significant decreases in rainfall during the 21st century (low to medium confidence).

Before stabilization of greenhouse gas (GHG) concentrations, the north-south temperature gradient in mid-southern latitudes is expected to increase (medium to high confidence), strengthening the westerlies and the associated west-to-east gradient of rainfall across Tasmania and New Zealand. Following stabilization of GHG concentrations, these trends would be reversed (medium confidence).

Water Supply and Hydrology: In some areas, water resources already are stressed and are highly vulnerable, with intense competition for water supply. This is especially so with respect to salinization (parts of Australia) and competition for water between agriculture, power generation, urban areas, and environmental flows (high confidence). Increased evaporation and possible decreases of rainfall in many areas would adversely affect water supply, agriculture, and the survival and reproduction of key species in parts of Australia and New Zealand (medium confidence).

Ecosystems and Conservation: Warming of 1°C would threaten the survival of species currently growing near the upper limit of their temperature range, notably in some Australian alpine regions that already are near these limits, as well as in the southwest of western Australia. Other species that have restricted climatic niches and are unable to migrate because of fragmentation of the landscape, soil differences, or topography could become endangered or extinct. Other ecosystems that are particularly threatened by climate change include coral reefs (Australia) and freshwater wetlands in the coastal zone and inland.

Food and Fiber: Agricultural activities are particularly vulnerable to regional reductions in rainfall in southwest and inland Australia (medium confidence) and eastern New Zealand. Drought frequency and consequent stresses on agriculture are likely to increase in parts of Australia and New Zealand as a result of higher temperatures and possibly more frequent El Niños (medium confidence). Enhanced plant growth and water-use efficiency (WUE) resulting from carbon dioxide (CO_2) increases may provide initial benefits that offset any negative impacts from climate change (medium confidence), although the balance is expected to become negative with warmings in excess of 2–4°C and associated rainfall decreases (medium confidence). Reliance on exports of agricultural and forest products makes the region sensitive to changes in commodity prices induced by changes in climate elsewhere.

Australian and New Zealand fisheries are influenced by the extent and location of nutrient upwellings governed by prevailing winds and boundary currents. In addition, ENSO influences recruitment of some fish species and the incidence of toxic algal blooms. There is as yet insufficient knowledge about impacts of climate changes on regional ocean currents and about physical-biological linkages to enable confident predictions of changes in fisheries productivity.

Settlements, Industry, and Human Health: Marked trends to greater population and investment in exposed coastal regions are increasing vulnerability to tropical cyclones and storm surges. Thus, projected increases in tropical cyclone intensity and possible changes in their location-specific frequency, along with sea-level rise, would have major impacts—notably, increased storm-surge heights for a given return period (medium to high confidence). Increased frequency of high-intensity rainfall would increase flood damages to settlements and infrastructure (medium confidence). There is high confidence that projected climate changes will enhance the spread of some disease vectors, thereby increasing the potential for disease outbreaks, despite existing biosecurity and health services.

Vulnerability and Adaptation: Climate change will add to existing stresses on achievement of sustainable land use and conservation of terrestrial and aquatic biodiversity. These stresses include invasion by exotic animal and plant species, degradation and fragmentation of natural ecosystems through agricultural and urban development, dryland salinization

(Australia), removal of forest cover (Australia and New Zealand), and competition for scarce water resources. Within both countries there are economically and socially disadvantaged groups of people, especially indigenous peoples, that are particularly vulnerable to additional stresses on health and living conditions induced by climate change. Major exacerbating problems include rapid population and infrastructure growth in vulnerable coastal areas, inappropriate use of water resources, and complex institutional arrangements. Adaptation to climate change, as a means of maximizing gains and minimizing losses, is important for Australia and New Zealand but is relatively little explored. Options include improving water-use efficiency and effective trading mechanisms for water; more appropriate land-use policies; provision of climate information and seasonal forecasts to land users, to help them manage for climate variability and change; improved crop cultivars; revised engineering standards and zoning for infrastructure development; and improved biosecurity and health services. Such measures often will have other benefits, but they also may have costs and limits.

Integrated Assessments: Comprehensive cross-sectoral estimates of net climate change impact costs for various GHG emission scenarios, as well as for different societal scenarios, are not yet available. Confidence remains very low in the previously reported (Basher *et al*., 1998) estimate for Australia and New Zealand of -1.2 to -3.8% of gross domestic product for an equivalent doubling of CO_2 concentrations. This out-of-date estimate did not account for many currently identified effects and adaptations.

Summary: Australia has significant vulnerability to changes in temperature and precipitation projected for the next 50–100 years (very high confidence) because it already has extensive arid and semi-arid areas and lies largely in the tropics and subtropics. New Zealand, a smaller and more mountainous country with a generally more temperate maritime climate, may be more resilient to climate changes than Australia, although considerable regional vulnerability remains (medium confidence).

12.1. The Australasian Region

12.1.1. Overview

Australasia is defined here as Australia, New Zealand, and their outlying tropical and mid-latitude islands. Australia is a large, relatively flat continent reaching from the tropics to mid-latitudes, with relatively nutrient-poor soils, a very arid interior, and rainfall that varies substantially on seasonal, annual, and decadal time scales, whereas New Zealand is much smaller, mountainous, and mostly well-watered. The ecosystems of both countries contain a large proportion of endemic species, reflecting their long evolutionary history and isolation from other land masses. They have been subject to significant human influences, before and after European settlement 200 years ago.

The region's climate is strongly influenced by the surrounding oceans. Key climatic features include tropical cyclones and monsoons in northern Australia; migratory mid-latitude storm systems in the south, including New Zealand; and the ENSO phenomenon, which causes floods and prolonged droughts, especially in eastern Australia.

The total land area is 8 million km^2, and the population is approximately 22 million. Much of the region is very sparsely populated; most people (85%) live in a relatively small number of coastal cities and towns. Both countries have significant populations of indigenous peoples who generally have lower economic and health status. The two countries have developed economies and are members of the Organisation for Economic Cooperation and Development (OECD); unlike other OECD countries, however, their export trade is dominated by commodity-based industries of agriculture and mining.

12.1.2. Previous Work

The Australasian chapter (Basher *et al.*, 1998) of the IPCC *Special Report on Regional Impacts of Climate Change* (RICC) (IPCC, 1998) provides an extensive assessment of likely climate change impacts and adaptation options for Australia and New Zealand, based on work published until early 1998. That report concludes that Australia's relatively low latitude makes it particularly vulnerable through impacts on its scarce water resources and crops that presently are growing near or above their optimum temperatures, whereas New Zealand—a cooler, wetter, mid-latitude country—may gain some benefit from the ready availability of suitable crops and a likely increase in agricultural production with regional warming. Nevertheless, a wide range of situations in which vulnerability was thought to be moderate to high were identified for both countries—particularly for ecosystems, hydrology, coastal zones, settlements and industry, and health. Indirect local impacts from possible climatically driven changes in international conditions—notably commodity prices and international trade—also was identified as a major issue in the 1998 report, as well as by the New Zealand Climate Change Programme (1990). Key points from Basher *et al.* (1998) follow.

Climate and Climate Trends: Climate trends were reported to be consistent with those in other parts of the world, with mean temperature increases of as much as 0.1°C per decade over the past century, a faster increase in nighttime than daytime temperatures, and sea level rising an average of about 20 mm per decade over the past 50 years. Increases in average rainfall and the frequency of heavy rainfalls were reported for large areas of Australia.

Climate Scenarios: Australian scenarios reported for 2030 exhibited temperature increases of 0.3–1.4°C, uncertain overall rainfall decrease of as much as 10%, and more high-intensity rainfall events. Projected changes for 2070 were about twice the 2030 changes. New Zealand projections included similar temperature increases, as well as stronger westerly air flow, with resulting precipitation increases in the west and decreases in the east.

Water Supply and Hydrology: Possible overall reduction in runoff, with changes in soil moisture and runoff varying considerably from place to place but reaching as much as ±20%, was suggested for parts of Australia by 2030. Sharpened competition was expected among water users, with the large Murray-Darling Basin river system facing strong constraints. Enhanced groundwater recharge and dam-filling events were expected from more frequent high-rainfall events, which also were expected to increase flooding, landslides, and erosion. A reduced snow season was expected to decrease the viability of the ski industry, although it would provide seasonally smoother hydroelectricity generation in New Zealand.

Ecosystems and Conservation: Significant potential impacts identified on Australasian land-based ecosystems included alteration in soil characteristics, water and nutrient cycling, plant productivity, species interactions, and ecosystem composition and function, exacerbated by any increases in fire occurrence and insect outbreaks. Aquatic systems would be affected by changes in runoff, river flow, and associated transport of nutrients, wastes, and sediments. These changes and sea-level rise would affect estuaries and mangroves. Australia's coral reefs were considered to be vulnerable to temperature-induced bleaching and possibly to sea-level rise and weather change.

Food and Fiber: Direct impacts on agriculture from CO_2 increases and climate changes were expected to vary widely in space and time, with perhaps beneficial effects early in the 21st century, followed by more detrimental effects in parts of Australia as warming increases. Any changes in global production and hence international food commodity prices would have major economic impacts. The net impact on production forestry from changes in tree productivity, forest operational conditions, weeds, disease, and wildfire incidence was not clear. The impact on fisheries could not be confidently predicted.

Settlements and Industry: Possible changes were noted in the frequency and magnitude of climatic "natural disaster" events affecting economically important infrastructure. Likely impacts of climate change were identified on water and air quality, water supply and drainage, waste disposal, energy production, transport operations, insurance, and tourism.

Human Health: Increases were expected in heat-stress mortality (particularly in Australia), the incidence of tropical vector-borne diseases such as dengue, and urban pollution-related respiratory problems.

Adaptation Potential and Vulnerability: Some of the region's ecosystems were identified as very vulnerable, with fragmentation and alteration of landscape by urban and agricultural development limiting natural adaptability. Land-use management was the primary adaptation option identified. Although coral reefs were identified as vulnerable, it was suggested that they might be able to keep pace with sea-level rise.

Techniques that already provide considerable adaptability of agriculture to existing climate variability may apply to climate change over the next few decades. However, at longer time horizons the climate was expected to become less favorable to agricultural production in Australia, leading to increased vulnerability. Scientifically based integrated fisheries and coastal zone management were regarded as principal adaptation options for fisheries.

Adaptation options identified for settlements and infrastructure included integrated catchment management, changes to water pricing systems, water efficiency initiatives, building or modifying engineering structures, relocation of buildings, and urban planning and management. Low-lying coastal settlements were regarded as highly vulnerable to high sea level and storm events. Adaptation options included integrated coastal zone management (ICZM); redesign, rebuilding, or relocation of capital assets; and protection of beaches and dunes. New Zealand is exposed to impacts on its Pacific island territories, including the eventual possibility of having to accept environmental refugees.

A moderate degree of vulnerability was identified for human health, with adaptation responses including strengthening existing public health infrastructure and meeting the needs of vulnerable groups such as isolated communities and the poor.

12.1.3. Socioeconomic Trends

The region's population is growing at a rate of about 1.2% yr^{-1}, approximately equally from natural increase and immigration. The population is progressively aging, in line with other OECD countries. Health status is improving, but indigenous peoples lag significantly. The main population centers are growing faster than rural areas. Australian lower latitude coastal zones are developing two to three times faster than the Australian average (see Section 12.6.4), for urban/suburban uses and for recreation and tourism. In New Zealand, there is a steady internal migration northward to Auckland.

Agricultural commodity prices have tended to fall, but yields per hectare have risen, and farm sizes and total volume of production have increased (ABARE, 1997; Wilson and Johnson, 1997). Average return on agricultural assets is low. Service industries are an increasing fraction of all industry, and there is a trend toward more intensive agriculture and forestry and to diversification of rural land use, including specialty crops and tourism. There is increasing competition for water in areas of low rainfall where irrigation is essential to intensive cropping; urban demands are rising quickly, and water is needed to maintain natural ecosystems (Hassall and Associates, *et al.*, 1998). Tourism is a major growth industry that is increasing the pressure on areas of attractions such as coastal zones and reefs.

Environmental concerns include air and water pollution from urban industries, land transport, and intensive farming and related processing and soil erosion, rising water tables, and salinization. Environmental management increasingly is based on the principle of sustainable management, as enshrined in New Zealand's Resource Management Act, and an integrated approach to environmental impacts in both countries. A major trend to a "user pays" principle and, especially in Australia, to market-driven water rights, with caps on irrigation supplies, is causing significant changes in rural industry. However, there still are many instances, particularly in coastal management, where these principles are not applied.

12.1.4. Climate Trends

Trends identified in the region continue to be generally consistent with those elsewhere in the world. Research on regional trends has been summarized in Salinger *et al*. (1996) and in specific studies by Plummer (1996), Torok and Nicholls (1996), Holbrook and Bindoff (1997, 2000), Lavery *et al*. (1997), Plummer *et al.* (1997), Zheng *et al.* (1997), McKeon *et al.* (1998), Collins and Della-Marta (1999), Hennessy *et al.* (1999), and Plummer *et al.* (1999).

Mean temperatures have risen by 0.05–0.1ºC per decade over the past century, with a commensurate increase in the frequency of very warm days and a decrease in the frequency of frosts and very cold days (Plummer *et al*., 1999; Collins *et al*., 2000). Nighttime temperatures have risen faster than daytime temperatures; hence, the diurnal temperature range has decreased noticeably in most places. The past decade has seen the highest recorded mean annual temperatures.

Trends in rainfall are less clear. Australian annual mean rainfall has increased by a marginally significant amount over the past century (Collins and Della-Marta, 1999; Hennessy *et al*., 1999). However, increases in the frequency of heavy rainfalls and average rainfall are significant in many parts of Australia. Average rainfall has increased most in the northwest and southeast quadrants (Collins and Della-Marta, 1999). The largest and most statistically significant change has been a decline in rainfall in the winter-rainfall-dominated region of the far southwest of western Australia, where in the period 1910–1995, winter (June-July-August, JJA) rainfall declined by 25%, mainly during the 1960s and 1970s. Previous studies (Wright, 1974;

Allan and Haylock, 1993; Yu and Neil, 1993), as well as a more recent one (Smith *et al*., 2000), have noted this decrease and attribute it to atmospheric circulation changes, predominantly resulting from natural variability.

There are marked interdecadal variations over northern and eastern Australia in summer half-year rainfall, which are dominated by ENSO-induced variations (Power *et al*., 1999a). There also are clear interannual and decadal variations in central and eastern Australian rainfall associated with Indian and Pacific Ocean sea surface temperatures (SSTs) (Power *et al.*, 1999b). Some of the regional linear trends observed during the past century merely may reflect a particular pattern of decadal variation. Thus, the high degree of decadal variability may enhance or obscure a signal that is related to climatic change for several decades. A growing body of evidence is being obtained about past climate variability from coral cores (e.g., Lough and Barnes, 1997; Isdale *et al.*, 1998; Quinn *et al.*, 1998).

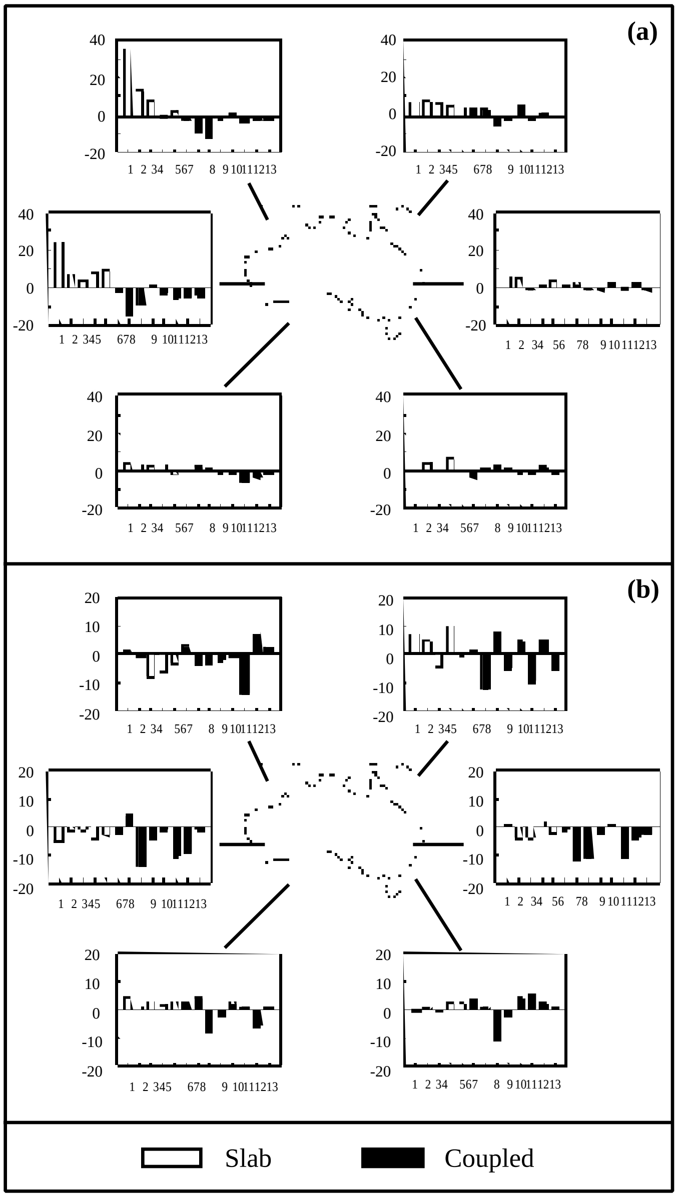

Figure 12-1: Enhanced greenhouse changes in rainfall (as % change per °C of global warming) for five slab-ocean GCM simulations (open bars) and eight coupled ocean-atmosphere GCM simulations (full bars), for six subregions of Australia in (a) summer (DJF) and (b) winter (JJA) Source: Whetton *et al*., 2001 (where individual models are identified). Spatial patterns and scatter plots are given for most of the same coupled models in Hulme and Sheard (1999) and Carter *et al*. (2000).

The strength of the relationship between eastern Australian climate and ENSO has been observed to vary over the past century. This seems to be linked to longer term climate oscillations such as the North Pacific Decadal Oscillation (NPDO) (e.g., Power *et al.*, 1999a). Salinger and Mullan (1999) examined the 20-year periods before and after 1977 and showed increases after 1977 (some statistically significant) in mean rainfall for New Zealand's west coast, associated with strengthening westerly winds. These fluctuations in rainfall are partially explained by the increase in El Niño conditions over recent decades. There is some evidence of long-term variations in the Australasian region in storm frequency and tropical cyclones (Nicholls *et al.*, 1996a; Radford *et al*., 1996; Hopkins and Holland, 1997; Leighton *et al.*, 1997). Nicholls *et al.* (1998) show that although there has been a decrease in tropical cyclone numbers from 1969 to 1996 in the Australian region (105°E to 160°E), there has been an increase in the frequency of intense tropical cyclones with central pressures of less than 970 hPa.

The average rise in sea level in the Australia/New Zealand region over the past 50 years is about 20 mm per decade (Rintoul *et al*., 1996; Salinger *et al.*, 1996), which is within the range of the current estimate of global sea-level rise (IPCC, 1996, WGI Section 7.2.1). However, the greater frequency and duration of El Niño episodes since the mid-1970s has reduced local New Zealand sea-level trends: The average sea-level change since 1975 at Auckland is close to zero (Bell *et al.*, 1999). There has been a weak warming trend in ocean temperatures to 100-m depth in the southwest Pacific (39°S to 49°S, 141°E to 179°E) of about 0.13°C during the 34-year period 1955–1988 (Holbrook and Bindoff, 1997), and there have been shorter period SST fluctuations associated with ENSO.

12.1.5. Climate Scenarios Used in Regional Studies

12.1.5.1. Spatial Patterns of Temperature and Rainfall

Most recent impact studies for Australia and New Zealand have been based on scenarios released by the Commonwealth Scientific and Industrial Research Organisation (CSIRO, 1996a) or the National Institute of Water and Atmosphere (NIWA—Renwick *et al.*, 1998b). The CSIRO (1996a) scenarios included two sets of rainfall scenarios that are based on results from equilibrium slab-ocean general circulation model (GCM) and transient coupled ocean-atmosphere GCM (AOGCM) simulations. Some impact and adaptation studies since RICC have used results from a 140-year simulation over the whole region that uses the CSIRO regional climate model (RCM) at

125-km resolution nested in the CSIRO Mark 2 coupled GCM run in transient mode from 1961 to 2100, as well as similar simulations at 60-km resolution over eastern Australia. Figure 12-1 (from Whetton *et al.*, 2001) summarizes results of slab-ocean and coupled AOGCM simulations of rainfall changes for various subregions of Australia in summer (December-January-February, DJF) and winter (JJA), respectively.

Figures 12-1a and 12-1b clearly show a variety of estimates for different model simulations; nevertheless, there is a tendency toward more decreases in winter rainfall in the southwest and the central eastern coast of Australia in the coupled model results than in the slab-ocean model results and a similar tendency for more agreement between coupled model results on less rainfall in the northwest and central west in summer.

In line with WGI conclusions, more recent scenarios, such as those of Hulme and Sheard (1999) and Carter *et al.* (2000) rely exclusively on coupled models; they also are based on the newer emissions scenarios from the IPCC's *Special Report on Emissions Scenarios* (SRES) rather than the IS92 scenarios described in IPCC (1996). This leads to some changes in the regional scenarios. According to Whetton (1999), the CSIRO (1996a) scenarios give warmings of 0.3–1.4°C in 2030 and 0.6–3.8°C in 2070 relative to 1990, compared to estimates by Hulme and Sheard (1999) of 0.8–3.9°C by the 2050s and 1.0–5.9°C in the 2080s, relative to the 1961–1990 averages. As discussed by Whetton (1999), both sets of scenarios use results from several coupled models, but the use of the SRES emissions scenarios leads to greater warmings in Hulme and Sheard (1999) than those that are based on the IS92 emission scenarios in CSIRO (1996). Nevertheless, the Hulme and Sheard (1999) results are preliminary in that they use scaled results from non-SRES simulations, rather than actual GCM simulations with SRES emissions.

Rainfall scenarios that are based on the coupled model results in CSIRO (1996a) show decreases of 0–8% in 2030 and 0–20% in 2070, except in southern Victoria and Tasmania in winter and eastern Australia in summer, where rainfall changes by –4 to +4% in 2030 and –10 to +10% in 2070. The Hulme and Sheard (1999) scenarios suggest that annual precipitation averaged over either northern or southern Australia is likely to change by –25 to +5%. Larger decreases are indicated for the 2080s and for some specific locations (e.g., a 50% decrease in parts of the southwest of western Australia in winter). This last finding suggests that even though the rainfall decrease in this region in the late 20th century was almost certainly dominated by natural variability (Smith *et al*., 2000), a decreasing trend resulting from the enhanced greenhouse effect may dominate in this region by the mid- to late 21st century.

It is important to note that changing from joint use of equilibrium slab-ocean GCM and transient coupled AOGCM results to exclusive reliance on coupled model results in the Australian scenarios leads to a marked narrowing of the uncertainty range in rainfall changes predicted for southern Australia, with a tendency to more negative changes on the mainland (see Figure 12-1; Hulme and Sheard, 1999; Carter *et al*., 2000). This means that the results of impact studies that used the wider range of rainfall scenarios, as in the CSIRO (1996a) scenarios (e.g., Schreider *et al*., 1996), should be reinterpreted to focus on the drier end of the previous range. This is consistent with more recent studies by Kothavala (1999) and Arnell (1999).

To summarize the rainfall results, drier conditions are anticipated for most of Australia over the 21st century. However, consistent with conclusions in WGI, an increase in heavy rainfall also is projected, even in regions with small decreases in mean rainfall. This is a result of a shift in the frequency distribution of daily rainfall toward fewer light and moderate events and more heavy events. This could lead to more droughts and more floods.

Recent Australian impact studies have tended to use regional scenarios of temperature and rainfall changes per degree of global warming, based on the CSIRO RCM transient simulations, scaled to the range of uncertainty of the global warming derived from the IPCC Second Assessment Report (SAR) range of scenarios. For example, Hennessy *et al*. (1998) gives scenarios for six regions of New South Wales (NSW), based on a 60-km resolution simulation. Ranges are given for estimated changes in maximum and minimum temperatures, summer days over 35°C, winter days below 0°C, seasonal mean rainfall changes, and numbers of extremely wet or dry seasons per decade. Statistical downscaling (discussed in detail in Chapter 3) has not been used extensively in Australia apart from work by Charles *et al*. (1999) on the southwest of western Australia. It should be noted that in some cases, RCM results may change the sign of rainfall changes derived from coarser resolution GCMs, because of local topographic and other effects (Whetton *et al*., 2001).

New Zealand scenarios reported in RICC (Basher *et al*., 1998) are based on statistical downscaling from equilibrium GCM runs with CO_2 held constant at twice its present concentration. Renwick *et al.* (1998b, 2000) also have downscaled equilibrium GCM simulations over New Zealand, using a nested RCM.

Akey factor in rainfall scenarios for New Zealand is the strength of the mid-latitude westerlies because of the strong orographic influence of the backbone mountain ranges lying across this flow (Wratt *et al.*, 1996). Earlier equilibrium slab-ocean GCM runs (applicable only long after stabilization of climate change) and the regional simulations obtained by downscaling them through statistical and nested modeling techniques predict a weakening of the westerlies across New Zealand, particularly in winter. As a result, downscaled equilibrium model runs predict that winter precipitation will remain constant or decrease slightly in the west but increase in Otago and Southland (Whetton *et al.*, 1996a; Renwick *et al.*, 2000). In contrast, transient coupled AOGCM runs suggest that over the next 100 years or more, the mean strength of the westerlies actually will increase in the New Zealand region, particularly in winter (Whetton *et al.*, 1996a; Russell and Rind, 1999; Mpelasoka *et al.*, 2001). As a result, downscaled transient model results predict that rainfalls will increase in the west of New Zealand but decrease in the east (Mullan *et al.*, 2001) as shown in Figure 12-2. Slightly larger temperature increases are predicted in the north of the country than in the south. Projected temporal changes in the westerlies before and after stabilization of climate also are likely to influence rainfall in southern Australia, especially in Tasmania.

GCM simulations extending beyond the stabilization of GHG concentrations indicate that global warming continues for centuries after stabilization of concentrations (Wigley, 1995; Whetton *et al*., 1998; TAR WGI Chapters 9 and 11) but at a much reduced rate as the oceans gradually catch up with the stabilized radiative forcing. Importantly for the Australasian region, simulated patterns of warming and rainfall changes in the southern hemisphere change dramatically after stabilization of GHG concentrations. This is because of a reversal of the lag in warming of the Southern Ocean relative to the rest of the globe. This lag increases up to stabilization but decreases after stabilization (Whetton *et al*., 1998), with consequent reversal of changes in the north-south temperature gradient, the mid-latitude westerlies, and associated rainfall patterns.

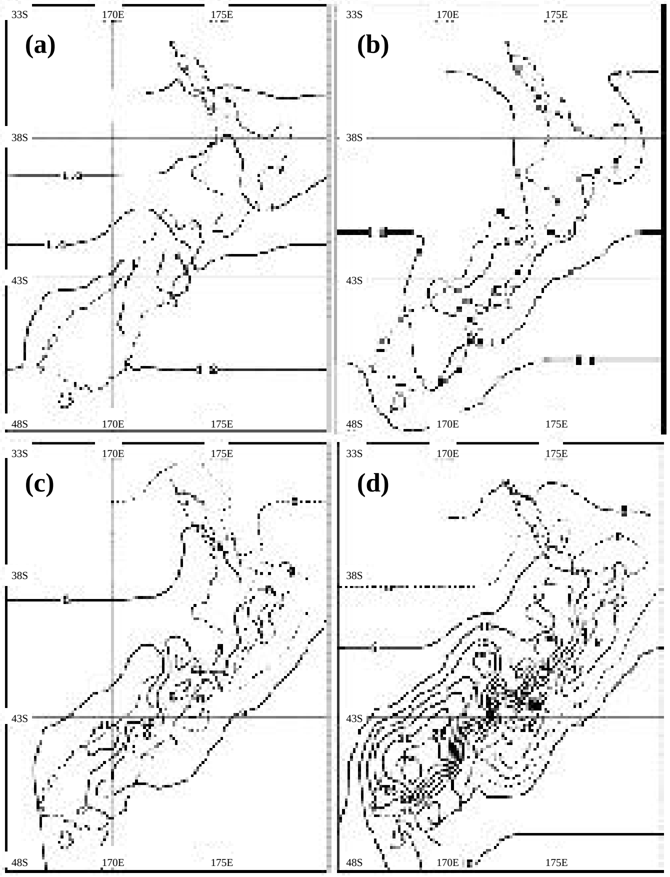

Figure 12-2: Scenarios for changes from the 1980s to the 2080s for New Zealand: (a) mean summer (DJF) temperature (°C), (b) mean winter (JJA) temperature (°C), (c) summer precipitation (%), and (d) winter precipitation (%). These plots were derived by averaging downscaled projections from four GCMs (CCC, CCSR, CSIRO9, and HadCM2) driven by CO_2 concentrations increasing at a compound rate of 1% yr^{-1}, plus specified sulfate aerosol concentrations (Mullan *et al.*, 2001).

12.1.5.2. Uncertainties and Probabilistic Scenarios

Some of the Australasian scenarios include uncertainty bands, based on the ranges of global warmings resulting from the IPCC IS92 emissions scenarios, the IPCC range of global sensitivity, or ranges of estimates of Australasian temperature or rainfall changes from different GCMs. Unquantified additional sources of uncertainty include changes in emission scenarios, such as to the new SRES scenarios; regional effects of biospheric feedback; and regional effects of global aerosol distributions. Quantification of potential changes in extreme events, tropical cyclones, and ENSO also are major uncertainties (see below), and uncertainty about the strength of the westerly circulation and hence rainfall regimes is a source of uncertainty for New Zealand. The modeled lag in warming in the Southern Ocean in the 20th century appears to be greater than that observed (Whetton *et al*., 1996a), but this has not yet been thoroughly analyzed. Other conceivable lower probability, high-impact changes (see Chapter 3) such as changes in ocean circulation, ENSO behavior, or tropical cyclones could have important regional impacts.

Probabilistic scenarios for risk and adaptation analyses (see Section 12.8.4), based on the quantifiable range of uncertainties, have been explored by CSIRO (Pittock, 1999; Jones, 2000; Pittock and Jones, 2000).

12.1.5.3 Changes in Extreme Events and Sea Level

Pittock *et al*. (1999) have summarized the past importance of extreme events for Australia and prospects for the future. Major climatic hazards arise in Australia and New Zealand from tropical cyclones, floods, droughts, windstorm, snowstorm, wildfires, landslides, hail, lightning, heat waves, frost, and storm surges. Events that are directly related to temperature are more predictable (more heat waves, fewer frosts) than those associated with wind and rain; Chapter 3 discusses relevant projections and confidence levels (see Table 3-10). The incidence of wildfire in Australia is expected to increase with global warming (Beer and Williams, 1995; Pittock *et al.*, 1999; Williams *et al.*, 2001), as is that of landslides and storm surges (the latter because of both higher mean sea level and increased storm intensities). Changes in hail and lightning frequencies are uncertain, although there are some arguments for expected increases (Price and Rind, 1994; McMaster, 1999; Pittock *et al.*, 1999).

More intense tropical cyclones in the Australian region (see Table 3-10; Walsh and Ryan, 2000) would have serious implications for storm-surge heights, wind damages, and flooding. If they were to travel further poleward (Walsh and Katzfey, 2000), they would be more likely to impact on coastal regions in the southwest of western Australia, southern Queensland, and the northern NSW coastal region, as well as northern parts of New Zealand. The locations of tropical cyclone genesis in the region are correlated with ENSO (Evans and Allan, 1992; Basher and Zheng, 1995), so any change in the mean state of the tropical Pacific may affect the risk of tropical cyclone occurrence in particular locations.

Mid-latitude storms also may increase in intensity (see Table 3-10), and their frequency and location could change—for example, as a result of changes in the westerlies and ENSO. This would impact return periods for mid-latutude storm surges, high winds, and other phenomena.

Interannual variability in ENSO leads to major floods and droughts in Australia and New Zealand. Such variations are expected to continue under enhanced greenhouse conditions, though possibly with greater hydrological extremes as a result of more intense rainfall in La Niña years and more intense drought resulting from higher rates of evaporation during El Niño years (Walsh *et al*., 1999). A more El Niño-like mean state of the tropical Pacific Ocean (see Table 3-10; Cai and Whetton, 2000) would imply greater drought frequency (Kothavala, 1999; Walsh *et al*., 2000), as does the drying trend found over the Murray-Darling Basin in recent AOGCM simulations (Arnell, 1999).

Mean sea level is expected to increase, with local and regional variations as a result of land-sea movements and changes to ocean currents and climatic forcing (see Chapter 3). In addition, local and regional meteorological forcing leads to temporary fluctuations in sea level and extreme events that may cause coastal inundation. In New Zealand, storm surges of as much as about 1 m are possible at open-coast locations (Heath, 1979; Bell *et al.*, 1999). Storm surges in tropical Australia can be several meters as a result of tropical cyclonic forcing and shallow continental shelfs (Hubbert and McInnes, 1999a,b; McInnes *et al*., 1999).

The actual height reached by a storm surge depends not only on the location and intensity of the storm but on its timing relative to the tides, coastal bathymetry and topography, and slower variations such as those from ENSO. The latter contribute to significant local sea-level variations around the coasts of Australia (Chiera *et al*., 1997) and New Zealand (Bell *et al*., 1999). In addition, any changes in storm intensities, frequencies, and locations will change the average time between surges of a given magnitude at particular locations.

12.1.5.4 New SRES Scenarios

Interim characterizations of regional climate changes to 2100 associated with the SRES emissions scenarios have been provided by Hulme and Sheard (1999) and Carter *et al.* (2000). However, they do not consider aerosol-induced spatial effects, and they use linear scaling of regional patterns of change from seven coupled GCM models, according to a range of global mean warmings generated using MAGICC (Wigley, 1995; Wigley *et al*., 1997).

Over Australia, these studies show warmings in the 2080s higher than the IS92 scenarios, with similar spatial patterns. In New Zealand, warmings in the 2080s are estimated to be from 0.5 to >2.0°C. Projected precipitation changes are large (>1 standard deviation of the simulated 30-year variability) over much of southern Australia, with a decrease over the mainland in both summer and winter and an increase over Tasmania in winter. Over the South Island of New Zealand, an increase is predicted. For the 2080s, projected decreases in annual rainfall in the southwest of western Australia range from about zero (B1 low scenario) to between 30 and 50% (A2 high scenario). Projected rainfall increases over the South Island of New Zealand of 0–10% (B1) to 10–20% (A2) should be regarded with caution because the AOGCM simulations do not fully incorporate the important influence of the Southern Alps on South Island rainfall patterns.

The SRES scenarios have not yet been applied in any detailed studies of impacts in the region. Unlike parts of the northern hemisphere, high regional concentrations of sulfate aerosols are not expected in the Australasian region under any accepted scenario, so any increase in warming resulting from reduced sulfate aerosols will be less over Australia and New Zealand than in some regions of the northern hemisphere.

To date, impact and vulnerability studies in Australia and New Zealand in general have not taken account of specific socioeconomic scenarios for the future, such as those laid out in the SRES. Thus, vulnerabilities have been based on projected climate change impacts and adaptation, assuming the present socioeconomic situation, in some cases with a qualitative allowance for expected socioeconomic trends (e.g., increased competition for water supplies, increased population and investment in coastal zones).

12.2. Key Regional Concerns

This section summarizes some key regional concerns regarding vulnerability to climate change and impacts in Australia and New Zealand. They have not been prioritized. Supporting details and references are provided in Sections 12.3 through 12.8.

Drought, Flood, and Water Supply: Climate variability is a major factor in the economies of both countries, principally through the flow-on effects of ENSO-related major droughts on agriculture. Farmers in drought-sensitive parts of both countries will be increasingly vulnerable if interannual droughts occur more frequently or are more intense in the future. Less secure water supplies would accentuate competition between users and threaten allocations for environmental flows and future economic growth. Adelaide and Perth are the main cities with water supplies that are most vulnerable to climate change; increasing salinity in the Murray River is an increasing concern for Adelaide. Any increase in flood frequency would adversely affect the built environment. In New Zealand, floods and landslides are natural hazards that could increase in frequency and severity.

Ecosystem Uniqueness and Vulnerability: Australia and New Zealand have been isolated from the rest of the world for millions of years until relatively recent human settlement. Some species exhibit quite limited ranges of average climate. These two factors leave many of the region's ecosystems vulnerable to climatic change and to invasion by exotic animal and plant species introduced by human activity. This vulnerability has been exacerbated by fragmentation of ecosystems through land-use changes.

Coral Reefs: Australia has one of the greatest concentrations of coral reefs in the world. Rising sea level by itself may not be deleterious. However, the combination of sea-level rise with other induced stresses—notably, increasing atmospheric CO_2 (which leads to a decrease in calcification rates of corals); increasing sea temperatures, leading to coral bleaching; possibly increased riverine outflow events (low salinity and high pollution); and damage from tropical cyclones—may put much of this resource at risk.

Alpine Areas: In Australia, significant warming will raise snowlines, diminish the ski industry, and threaten alpine ecosystems. In New Zealand, snowline changes and the advance or retreat of glaciers also depend on changes in the strength and local orientation of mid-latitude westerlies. Options for relocation of the ski industry are limited by the relatively low altitude of Australia's alpine regions and by rugged terrain and conservation estate regulations in New Zealand.

Agricultural Commodities and Terms of Trade: A major fraction of exports from both Australia and New Zealand are agricultural and forestry products, production of which is sensitive to any changes in climate, water availability, CO_2 fertilization, and pests and diseases. Returns from these commodities could be affected by the projected increase in agricultural production in mid- to high-latitude northern hemisphere countries and resulting impacts on commodity prices and world trade.

Increasing Coastal and Tropical Exposure: Major population and economic growth in coastal areas, especially the tropical and subtropical east coast of Australia, are leading to greatly increased vulnerability to tropical cyclones and storm surges, as well as riverine and estuarine flooding. Rising sea level will accentuate these problems, as would any increase in storm intensities or a more poleward movement of tropical cyclones. Rising sea level also will increase the salinity of estuarine and coastal aquifer groundwater.

Indigenous People: In both countries, indigenous peoples (Aborigines and Torres Straits Islanders in Australia, Maori in New Zealand, as well as Pacific islanders) are among the most disadvantaged members of the population. They generally have lower incomes, and many live in isolated rural conditions or in the sometimes poorly serviced and low-lying margins of large towns and cities. They are more exposed to inadequate water supplies, climatic disasters, and thermal stress and are more vulnerable to an increase in the prevalence of pests and diseases.

12.3. Water Supply and Hydrology

12.3.1. Water Supply

Dry conditions in most parts of Australia tend to be associated with El Niño. The link between rainfall and streamflow and ENSO is statistically significant in most parts of eastern Australia (Chiew *et al.*, 1998; Power *et al.*, 1998). Relationships between river flows and ENSO also have been identified for some seasons in parts of New Zealand (McKerchar *et al*., 1998). Because of the relatively high variability of Australian rainfall, the storage capacities of Australia's large dams are about six times larger than those of European dams for the same mean annual streamflow and probability of water shortfall. In contrast, New Zealand's hydroelectricity system has a total storage capacity of about 6 weeks of national demand because of its higher and more reliable rainfall (Basher *et al*., 1998).

The Murray-Darling River basin is the largest in Australia and is heavily regulated by dams and weirs. About 40% of mean annual flow is used for human consumption, principally through irrigation; there is high interannual variability. Application of the CSIRO (1996a) scenarios, with their wide range of rainfall changes as a result of inclusion of both the older slab-ocean GCM and the more recent coupled AOGCM simulations, suggests a possible combination of small or larger decreases in mean annual rainfall, higher temperatures and evaporation, and a higher frequency of floods and droughts in northern Victorian rivers (Schreider *et al.*, 1996). A study of the Macquarie River basin in NSW indicates inflow reductions on the order of 10–30% for doubled CO_2 and reduced streamflows if irrigation demand remains constant or increases (Hassall and Associates *et al*., 1998). Adelaide and Perth traditionally have been regarded as the most vulnerable metropolitan areas to future water supply problems, including increasing levels of salinity (Schofield *et al.*, 1988; Williams, 1992; PMSEIC, 1998; MDBC, 1999), although Perth recently has decided to spend AU$275 million for drought-proofing (Boer, 2000). Water supplies are adequate for many coastal regions in Australia. However, drier inland areas are vulnerable to water shortages during the annual dry season and drought.

Studies by Kothavala (1999) and Arnell (1999)—using results from the U.S. National Center for Atmospheric Research (NCAR) Community Climate Model (CCMO) GCM and the HadCM2 and HadCM3 AOGCMs, respectively—show increases in drought across eastern and southern Australia. Kothavala found that the Palmer Drought Index showed longer and more severe drought in northeastern and southeastern Australia. Arnell (1999) found marked decreases in runoff over most of mainland Australia but some increases over Tasmania. For the Murray-Darling basin, he found decreases in mean flow by the 2050s ranging from about 12 to 35%, with decreases in the magnitude of 10-year maximum and minimum monthly runoff.

The only recent water supply study for New Zealand is that by Fowler (1999), based on the RSNZ (1988) and Mullan and Renwick (1990) regional climate change scenarios and three equilibrium slab-ocean GCM simulations. These models give scenarios of rainfall increases in the Auckland region, leading to the conclusion that changes in water resources most likely would be positive. Scenarios based on recent AOGCM simulations have yet to be evaluated.

Atolls and low-lying islands (e.g., some in the Torres Strait and in association with New Zealand) rely on rainwater or limited groundwater resources for water supplies. These resources are sensitive to climate variations and in some cases already are stressed by increasingly unsustainable demand and pollution caused by human activity. Saltwater intrusion into aquifers might occur through sea-level rise, more frequent storm events, possible reductions in rainfall, and increased water demand as a result of higher temperatures (see Basher *et al.*, 1998; Chapter 17).

12.3.2. Water Allocation and Policy

Until recently, water planning in Australia was driven by demand and controlled by engineers, not by economics (Smith, 1998b). This situation has changed with growing population and demand (rural and urban/industrial), including rapid growth in irrigation of high-value crops such as cotton and vineyards. There also is an increasing awareness of stress on riverine ecosystems as a result of reduced mean flows, lower peak flows, and increasing salinity and algal blooms. Higher temperatures and changed precipitation as a result of climate change generally would exacerbate these problems and sharpen competition among water users (e.g., see Hassall and Associates *et al*., 1998). In 1995, the Council of Australian Governments reviewed water resource policy in Australia and agreed to implement a strategic framework to achieve an efficient and sustainable water industry through processes to address water allocations, including provision of water for the environment and water-trading arrangements. The Agriculture and Resource Management Council of Australia and New Zealand subsequently commissioned a set of National Principles for the Provision of Water for Ecosystems, with the following stated goal: “To sustain and where necessary restore ecological processes and biodiversity of water-dependent ecosystems.” Implementation of water reforms and national principles has resulted in the definition of conceptual frameworks and practical methods for assessing the water requirements of environmental systems.

In Australia, flow recommendations commonly are developed after water infrastructure projects and dams have been in place for some time and environmental flows implemented in river systems that already are experiencing a modified or regulated flow regime (Arthington, 1998; Arthington *et al.*, 1998). This situation is most applicable to adaptation to climate change in existing regulated flow regimes.

The Australian National Principles require that provision of water for ecosystems should use the best scientific information available on the hydrological regimes necessary to sustain aquatic ecosystems. Ideally, environmental flow recommendations are based on establishment of quantitative relationships between flow characteristics and desired geomorphological, ecological, or water-quality outcomes. Methods are available to estimate flow-related habitat requirements of aquatic invertebrates, fish, and aquatic and riparian plants (e.g., wetted perimeter, transect methods, instream flow incremental methodology (IFIM)—see Kinhill, 1988). However, there are no standard methods for assessing flows that are relevant to maintenance of key life history processes. In the absence of robust biological indicators of response to flow regulation, recent research has advocated the use of statistical descriptors of flow regimes. These methods include maintenance of critical flow characteristics within one or two standard deviations of mean parameters (Richter *et al*., 1996).

In New Zealand, various pressures on riverine ecosystems have been recognized, including those from agriculture, urban usage and sewage, hydroelectricty and water supply dams, forestry and mining, and introduced pests and weeds. Management of water is covered by the Resource Management Act (RMA) of 1991. Under this Act, the intrinsic values of ecosystems, including their biodiversity and life-supporting capacity, must be considered. The emphasis has changed from multiple-use management to environmentally sustainable management (Taylor and Smith, 1997), and Maori values are explicitly recognized (Ministry for the Environment, 1999). Drought associated with ENSO has placed stress on water supplies in various parts of the country, and it is recognized that climate change could lead to further stresses, especially if there is an increase in the frequency of El Niño events (Taylor and Smith, 1997). The RMAprovides a statutory basis for integrated catchment management in that regional Councils control land use, water use, and water quality. Regional plans under which water is allocated have a term of only 10 years, allowing for review to adapt to issues such as river flow changes caused by climate change.

In the context of climate change, it is relevant to ask: How much can critical features of the flow regime be changed before the system becomes seriously stressed? Finding answers to this question for a range of Australian rivers is central to the assessment and management of water allocations to sustain water-dependent systems. Climate change has yet to be systematically injected into this process, but at least the mechanisms are now in place to develop appropriate water allocations and price incentives to use water to the best advantage. There also is scope for increased application of seasonal climate forecasts in water resources management, as a tool to aid adaptation to climate variability.

12.3.3. Inland and Coastal Salinization

Natural salinity and high water tables have been present in Australia for centuries. However, because of changes in land management—notably land clearing and irrigation—salinity is now a major environmental issue in Australia (Ghassemi *et al*., 1995; MDBC, 1999). About 2.5 Mha are affected in Australia, with the potential for this to increase to 12.5 Mha in the next 50 years (PMSEIC, 1999). Much of this area covers otherwise productive agricultural land. The area damaged by salinity to date represents about 4.5% of presently cultivated land, and known costs include US$130 million annually in lost agricultural production, US$100 million annually in damage to infrastructure (such as roads, fencing, and pipes); and at least US$40 million in lost environmental assets (Watson *et al.*, 1997; PMSEIC, 1998). The average salinity of the lower Murray River (from which Adelaide draws much of its water supply) is expected to exceed the 800 EC threshold for desirable drinking water about 50% of the time by 2020.

Although climate is a key factor affecting the rate of salinization and the severity of impacts, a comprehensive assessment of the effects of climate change on this problem has not yet been carried out. Revegetation policies and associated carbon credit motivational policies designed to increase carbon sinks are likely to have a significant impact on recharge. However, global warming and dryland salinity policies need to be coordinated to maximize synergistic impacts.

In many coastal areas and oceanic islands, development and management of fresh groundwater resources are seriously constrained by the presence of seawater intrusion. Seawater intrusion is a natural phenomenon that occurs as a consequence of the density contrast between fresh and saline groundwater. If conditions remain unperturbed, the saline water body will remain stationary unless it moves under tidal influences. However, when there is pumping of freshwater, sea-level change, or changing recharge conditions, the saline body will gradually move until a new equilibrium condition is achieved (Ghassemi *et al.*, 1996). If the sea level rises to its “best-guess” or extreme predicted value over the next century, this would significantly increase intrusion of seawater in coastal and island aquifers.

12.3.4. Water Quality

Water quality would be affected by changes in biota, particularly microfauna and flora; water temperature; CO_2 concentration; transport processes that place water, sediment, and chemicals in streams and aquifers; and the timing and volume of water flow. More intense rainfall events would increase fast runoff, soil erosion, and sediment loadings, and further deforestation and urbanization would tend to increase runoff amounts and flood wave speed. These effects would increase the risk of flash flooding, sediment load, and pollution (Basher *et al.*, 1998). On the other hand, increases in plantation and farm forestry—in part for carbon sequestration and greenhouse mitigation purposes—would tend to reduce soil erosion and sediment loads.

Eutrophication is a major water quality problem in Australia (State of the Environment, 1996). This is a natural process, but it has been greatly accelerated in Australia by human activities, including sewage effluent and runoff from animal farms, irrigation, and stormwater. Low flow, abundant light, clear water, and warmth all encourage algal growth, which affects the taste and odor of water and can be toxic to animals, fish, and humans. Thus, local climate warming and the potential for reduced streamflow may lead to increased risk of eutrophication.

12.4. Ecosystems and Conservation

12.4.1. Introduction

Until recent settlement, Australia and New Zealand were isolated for millions of years, and their ecosystems have evolved to cope with unique climate and biological circumstances (Kemp, 1981; Nix, 1981). Despite large year-to-year climatic variability, many Australian terrestrial species have quite limited ranges of long-term average climate, on the order or 1–2°C temperature and 20% in rainfall (Hughes *et al.*, 1996; Pouliquen-Young and Newman, 1999). Thus, these ecosystems are vulnerable to climatic change, as well as invasion by exotic animals and plants.

Rapid land clearance and subsequent land-use change have been occurring as a result of human activity over the past 500–1,000 years in New Zealand (McGlone, 1989; Wilmshurst, 1997) and, in Australia, subsequent to Aboriginal arrival tens of thousands of years ago—and especially since European settlers arrived 200 years ago. This has led to loss of biodiversity in many ecosystems as well as loss of some ecosystems as a whole. One of the major impacts has been an increase in weedy species in both countries. This is likely to continue and be exacerbated by climate change. Land-use change also has led to fragmentation of ecosystems and to salinization through rising water tables. These trends can inhibit natural adaptation to climate change via the dispersal/migration response. Systems therefore may be more vulnerable, and some might become extinct. For example, Mitchell and Williams (1996) have noted that habitat that is climatically suitable for the long-lived New Zealand kauri tree *Agathis australis* under a 4°C warming scenario would be at least 150 km from the nearest extant population. They suggest that survival of this species may require human intervention and relocation. Similar problems have been identified by Pouliquen-Young and Newman (1999) in relation to fragmented habitat for endangered species in the southwest of western Australia.

Many of the region’s wetlands, riverine environments, and coastal and marine systems also are sensitive to climate variations and changes. A key issue is the effect on Australia’s coral reefs of greenhouse-related stresses in addition to nonclimatic features such as overexploitation and increasing pollution and turbidity of coastal waters from sediment loading, fertilizers, pesticides, and herbicides (Larcombe *et al*., 1996).

12.4.2. Forests and Woodlands

In Australia, some 50% of the forest cover in existence at the time of European settlement still exists, although about half of that has been logged (Graetz *et al.*, 1995; State of the Environment, 1996). Pressures on forests and woodlands as a whole are likely to decrease as a result of recent legislation relating to protection of forests in some Australian states, and as interest in carbon sequestration increases. In New Zealand (Taylor and Smith, 1987), 25% of the original forest cover remains, with 77% in the conservation estate, 21% in private hands, and 2% state owned. Legal constraints on native wood production mean that only about 4% currently is managed for production, and clear-felling without replacement has virtually ceased.

The present temperature range of 25% of Australian Eucalyptus trees is less than 1°C in mean annual temperature (Hughes *et al*., 1996). Similarly, 23% have ranges of mean annual rainfall of less than 20% variation. The actual climate tolerances of many species are wider than the climate envelope they currently occupy and may be affected by increasing CO_2 concentrations, which change photosynthetic rates and water-use efficiency (WUE) and may affect the temperature response (Curtis, 1996). Such changes from increasing CO_2 would be moderated by nutrient stress and other stressors that are prevalent across Australian forests. Nevertheless, if present-day boundaries even approximately reflect actual thermal or rainfall tolerances, substantial changes in Australian native forests may be expected with climate change. Howden and Gorman (1999) suggest that adaptive responses would include monitoring of key indicators, flexibility in reserve allocation, increased reserve areas, and reduced fragmentation.

In a forested area in western Australia that is listed as one of 25 global "biodiversity hotspots" for conservation priority by Myers *et al.* (2000), Pouliquen-Young and Newman (1999) used the BIOCLIM program (Busby, 1991) to generate a climatic envelope from the present distribution of species. They assessed the effects of three incremental temperature and rainfall scenarios on three species of frogs, 15 species of endangered or threatened mammals, 92 varieties of the plant genus *Dryandra*, and 27 varieties of *Acacia* in the southwest of western Australia. The scenarios were based on the spatial pattern of change from the CSIRO RCM at 125-km resolution, scaled to the IS92 global scenarios. For plant species, suitability of soils also was considered. The results indicate that most species would suffer dramatic decreases in range with climate warming; all of the frog and mammal species studied would be restricted to small areas or would disappear with 0.5°C global-average warming above present annual averages, as would 28% of the *Dryandra* species and one *Acacia*. At 2°C global average warming, 66% of the *Dryandra* species, as well as all of the *Acacia*, would disappear. Adaptation opportunities were considered minimal, with some gain from linking present conservation reserves and reintroducing endangered species into a range of climatic zones.

Studies of the current distribution of New Zealand canopy trees in relation to climate suggest that major range changes can be expected with warming (Whitehead *et al*., 1992; Leathwick *et al.* 1996; Mitchell and Williams, 1996). Trees in the highly diverse northern and lowland forests (e.g., *Beilschmiedia tawa*) are likely to expand their ranges southward and to higher altitudes. The extensive upland *Nothofagus* forests are likely to be invaded by broad-leafed species. Few tree species are confined to cool southern climates; those that are have a wide altitudinal range available for adjustment of their distribution, so no extinctions are expected. Most concern centers on the ability of tree species to achieve new distributions rapidly enough in a fragmented landscape, as well as invasion of natural intact forests by exotic tree, shrub, and liana species that are adapted to warm temperate or subtropical climates.

12.4.3. Rangelands

In Australia, rangelands are important for meat and wool production. In their natural state, rangelands are adapted to relatively large short-term variations in climatic conditions (mainly rainfall and temperature). However, they are under stress from human activity, mostly as a result of animal production, introduced animals such as rabbits, inappropriate management, and interactions between all of these factors (Abel *et al.*, 2000). These stresses, in combination with climatic factors, have led to problems of land degradation, salinization, and woody weed invasion and subsequent decreases in food production. In some cases, native dominant species (mostly plants) have been replaced by exotic species, leading to a decrease in population of many native animal species. Woody weed invasion also has changed the fire regime through formation of "thickets" that do not allow fires through, partly as a result of the fire resistance of some species (Noble *et al*., 1996). Some Australian rangelands also are vulnerable to salinization resulting from rising water tables from irrigation and loss of native vegetation (see Section 12.3).

New Zealand rangelands are used predominantly for sheep grazing. Intensive use of indigenous grasslands and shrublands on land cleared of trees in the 19th century has increased vulnerability to invasion, especially by woody weeds (pine, broom, gorse, etc.) and herbaceous weeds (hawkweed, thistles, and subtropical grasses). Weed invasions are unlikely to further increase the susceptibility of the system to climatic disruptions but could themselves be accelerated by warming or increased climatic variability. Fire is now strictly regulated, although rangeland fires remain a serious problem, especially in ENSO drought years. Rangelands—in particular, in drier areas of eastern South Island—have many problems, including animal and plant pests and declining profitability of farming, leading to a decline in management and fertilizer inputs.

Increased CO_2 is likely to have beneficial effects for native pastures, with possible nitrogen limitation and increased subsoil drainage (Howden *et al.*, 1999d). Runoff and groundwater recharge also could increase (Krysanova *et al.*, 1999). This could lead to increased salinization problems in areas that are susceptible. However, decreases in rainfall in excess of about 10% at the time of CO_2 doubling would dominate over the CO_2 fertilization effect and lead to a decline in pasture productivity. This is more likely in the latest climate change scenarios that are based on coupled AOGCM results. Howden *et al.* (1999d) conclude that a doubling of CO_2 concentrations will result in only limited changes in the distribution of C_3 and C_4 grasses and that such changes will be moderated by warmer temperatures.

12.4.4. Alpine Systems

Basher *et al*. (1998) conclude that alpine systems are among the most vulnerable systems in the region. Despite the fact that they cover only a small area, they are important for many plant and animal species, many of which are listed as threatened. These systems also are under pressure from tourism activity. The Australian Alps are relatively low altitude (maximum about 2,000 m), and much of the Alpine ecosystem area and ski fields are marginal. Most year-to-year variability is related to large fluctuations in precipitation, but interannual temperature variations are small compared to warming anticipated in the 21st century. Studies by Hewitt (1994), Whetton *et al.* (1996b), and Whetton (1998) all point to a high degree of sensitivity of seasonal snow cover duration and depth. For Australia, Whetton (1998) estimates, for the full range of CSIRO (1996a) scenarios, an 18–66% reduction in the total area of snow cover by 2030 and a 39–96% reduction by 2070. This would seriously affect the range of certain alpine ecosystems and species (Bennett *et al*., 1991). Decreases in precipitation and increased fire danger also would affect alpine ecosystems adversely.

There seems to be little opportunity for adaptation by alpine ecosystems in Australia, which cannot retreat upward very far because of the limited height of Australian hills and mountains. There are various options for the rapidly expanding mountain-based recreation industry, including increased summer recreation and artificial snowmaking. These adaptations would increase stress on alpine ecosystems and water resources.

The New Zealand Alps are of higher altitude (up to 3,700 m); about 9% of the New Zealand landmass is above the treeline. A large number of species (for example, 25% of vascular plants), which often are highly distinctive, grow there. Despite a 0.5°C rise in New Zealand's mean annual temperatures since the 1860s, there has been no significant rise in the treeline or shrubland expansion (Wardle and Coleman, 1992), and it seems unlikely that there will be any significant threat to alpine ecosystems from warming in the medium term.

12.4.5. Wetlands

The Australian State of the Environment Report (1996) states, "Wetlands continue to be under threat, and large numbers are already destroyed." For example, Johnson *et al.* (1999) estimate wetland loss of about 70% in the Herbert River catchment of Northern Queensland between 1943 and 1996. Wetland loss is caused by many processes, including water storage; hydroelectric and irrigation schemes; dams, weirs, and river management works; desnagging and channelization; changes to flow, water level, and thermal regimes; removal of instream cover; increased siltation; toxic pollution and destruction of nursery and spawning or breeding areas (Jackson, 1997); and use of wetlands for agriculture (Johnson *et al.*, 1999). Climate change will add to these factors through changes in inflow and increased water losses.

Specific threats to wetlands from climate change and sea-level rise have been studied as part of a national vulnerability assessment (Waterman, 1996). The best example is provided for Kakadu National Park in northern Australia. There are fears that World Heritage and Ramsar-recognized freshwater wetlands in this park could become saline, given current expectations of sea-level rise and climate change (Bayliss *et al.,* 1997; Eliot *et al*., 1999). Although this analysis is supported by a large data resource, it is speculative, and efforts to develop more definite monitoring tools are needed. However, it does raise the possibility that many other Australian coastal wetlands could be similarly affected. Some of these wetlands may be unable to migrate upstream because of physical barriers in the landscape.

Many inland wetlands are subject to reduced frequency of filling as a result of water diversion for irrigation, and they also may be seriously affected by reductions in seasonal or annual rainfalls in the catchments as a result of climate change (Hassall and Associates *et al*., 1998). This may threaten the reproduction of migratory birds (some species of which already are under threat), which rely on wetlands for their breeding cycle (Kingsford and Thomas, 1995; Kingsford and Johnson, 1998; Kingsford *et al*., 1999). Large decreases in inflow predicted for the Macquarie River and several rivers in northern Victoria by Hassall and Associates *et al*. (1998) and Schreider *et al*. (1996, 1997) for scenarios that are consistent with the latest AOGCM simulations would have major impacts on wetland ecosystems.

Wetlands in New Zealand are the most threatened ecosystems; they have declined by 85% since European settlement (Stephenson, 1983). The vast majority have been drained or irretrievably modified by fire, grazing, flood control works, reclamation, or creation of reservoirs. Eutrophification, weed invasion, and pollution have greatly reduced their biodiversity (Taylor and Smith, 1997). More than 50% of the 73 significant wetlands that meet the Ramsar Convention standards for international wetlands are in coastal districts and will be impacted by rising sea levels. Most important wetlands are in highly urbanized or productive landscape settings and therefore have limited options for adaptation to decreased size or increased salinization.

12.4.6. Riverine Environments

Many Australian river systems, particularly in the southeast and southwest, have been degraded through diversion of water via dams, barrages, channels, and so forth, principally for irrigated agriculture. Many New Zealand rivers have been affected by hydroelectric generation; diversion of water for irrigation; agricultural, manufacturing, and urban pollution; and biotic invasion. Recent research has shown that river ecosystems are particularly sensitive to extremes in flow. Most research has been on the effects of flood flows. Droughts, as opposed to floods, have a slow onset and although recovery from floods by river flora and fauna is relatively rapid, recovery after droughts tends to be slow, may be incomplete, and may lag well behind the breaking of the drought (Lake, 2000). Floods and droughts interact with nutrient supply (Hildrew and Townsend, 1987; Biggs, 1996), so the effects of any possible changes in their frequency and magnitude need to be evaluated within the context of other human activities and climate-induced land-use change.

Current ranges of scenarios tend to suggest reductions in mean flow in many Australian rivers, similar to or greater than those in Schreider *et al*. (1997) and Hassall and Associates *et al.* (1998). In particular, any tendency toward more frequent or severe El Niño-like conditions beyond that already contained in the CSIRO (1996a) scenarios would further threaten many riverine and inland wetland systems in Australia and New Zealand. Findings of increased drought frequency and severity in eastern Australia under an NCAR CCMO transient simulation (Kothavala, 1999) and 12–35% reductions in mean flow by 2050 in the Murray-Darling basin by the 2050s in Arnell (1999), using results from the HadCM2 and HadCM3 GCM simulations, are cause for concern. Arnell (1999) found reductions in maximum and minimum flows. Walsh *et al.* (2000) found less severe increases in drought in Queensland, based on simulations with the CSIRO RCM nested in the CSIRO Mark 2 GCM.

Implications of these findings for riverine ecosystems and estuaries (Vance *et al*., 1998; Loneragan and Bunn, 1999) and possible adaptations have yet to be investigated, although reduced diversions from rivers to increase environmental flows is one possibility. This could be achieved through increased WUE, imposition of caps on water diversions, or water pricing and trading, but the latter two measures are controversial and would have strong implications for rural industry (e.g., see ABARE, 1999). Increased efficiency in water delivery for irrigation currently is the favored option for restoring environmental flows in the heavily depleted Snowy River in southeastern Australia.

12.4.7. Coastal and Marine Systems

Australia has some of the finest examples of coral reefs in the world, stretching for thousands of kilometers along the northwest and northeast coasts (Ellison, 1996). Coral reefs in the Australian region are subject to greenhouse-related stresses (see Chapter 6 for a summary), including increasingly frequent bleaching episodes, changes in sea level, and probable decreases in calcification rates as a result of changes in ocean chemistry.

Mass bleaching has occurred on several occasions in Australia's Great Barrier Reef (GBR) and elsewhere since the 1970s (Glynn, 1993; Hoegh-Guldberg *et al.*, 1997; Jones *et al.*, 1997; Wilkinson, 1998). Particularly widespread bleaching, leading to death of some corals, occurred globally in 1997–1998 in association with a major El Niño event. Bleaching was severe on the inner GBR but less severe on the outer reef (Wilkinson, 1998; Berkelmans and Oliver, 1999). This episode was associated with generally record-high SSTs over most of the GBR region. This was a result of global warming trends resulting from the enhanced greenhouse effect and regional summer warming from the El Niño event, the combined effects of which caused SSTs to exceed bleaching thresholds (Lough, 1999). Three independent databases support the view that 1997–1998 SST anomalies were the most extreme in the past 95 years and that average SSTs off the northeast coast of Australia have significantly increased from 1903 to 1994. Lowered seawater salinity as a result of flooding of major rivers between Ayr and Cooktown early in 1998 also is believed to have been a major factor in exacerbating the effects in the inshore GBR (Berkelmans and Oliver, 1999). Solar radiation, which is affected by changes in cloud cover and thus by El Niño, also may have been a factor (Brown, 1997; Berkelmans and Oliver, 1999).

Although warming in Australia's coral reef regions on average is expected to be slightly less than the global average, according to the SRES global warming scenarios it may be in the range of 2–5°C by 2100. This suggests that unless Australian coral reefs can adapt quickly to these higher temperatures, they will experience temperatures above present bleaching thresholds (Berkelmans and Willis, 1999) almost every year, well before the end of the 21st century (Hoegh-Guldberg, 1999). Hoegh-Guldberg (1999) notes that apparent thresholds for coral bleaching are higher in the northern GBR than further south, suggesting that some very long-term adaptation has occurred. Coral reef biota may be able to adapt, at least initially, by selection for the more heat-tolerant host and symbiont species and genotypes that survived the 1997–1998 summer and by colonization of damaged sites by more heat-resistant genotypes from higher latitudes arriving as planktonic larvae. However, it is generally believed that the rate and extent of adaptation will be much slower than would be necessary for reef biota to resist the frequency and severity of high SSTanomalies projected for the middle third of the 21st century (medium to high confidence). The most likely outlook is that mass bleaching, leading to death of corals, will become a more frequent event on Australian coral reefs in coming decades.

Increasing atmospheric CO_2 concentrations will decrease the carbonate concentration of the ocean, thereby reducing calcification rates of corals (Gattuso *et al.*, 1998, 1999; Kleypas *et al.*, 1999). This is complicated, however, by the effects of possible changes in light levels, freshwater discharge, current patterns, and temperature. For example, Lough and Barnes (2000) report a historic growth stimulus for the *Porites* coral that they correlate with increasing average SSTs. Thus, the net effect on Australian reefs up to 1980 appears to have been positive, but it is unclear whether decreased carbonate concentration resulting from rapidly increasing CO_2 concentration will outweigh the direct temperature effect later in the 21st century, especially if regional SSTs reach levels not experienced by the corals of the GBR during the Holocene.

As noted in Chapter 6, expected rates of sea-level rise to 2100 would not threaten healthy coral reefs (most Australian reefs) but could invigorate growth on reef flats. However, decreased calcification rates might reduce the potential ability of the reefs to keep up with rapid sea-level rise. Possible increases in tropical cyclone intensity with global warming also would impact coral reefs (high confidence), along with nonclimatic factors such as overexploitation and increasing pollution and turbidity of coastal waters by sediment loading, fertilizers, pesticides, and herbicides (Larcombe *et al.*, 1996). Climate change could affect riverine runoff and associated stresses of the reefs, including low-salinity episodes. Coupled with predicted rises in sea level and storminess, bleaching-induced coral death also could weaken the effectiveness of the reefs in protecting the Queensland coast and adversely affect the biodiversity of the reef complex.

On the whole, mangrove processes are less understood than those for coral reefs (Ellison, 1996). Mangroves occur on low-energy, sedimentary shorelines, generally between mean- and high-tide levels. Australian mangroves cover approximately 11,500 km^2 (Galloway, 1982). It is anticipated that they are highly vulnerable but also highly adaptable to climate change. Studies over glacial/interglacial cycles show that in the past mangroves have moved landward during periods of rising sea level (Woodroffe, 1993; Wolanski and Chappell, 1996; Mulrennan and Woodroffe, 1998). However, in many locations this will be inhibited now by coastal development. Coastal wetlands are thought to be nursery areas for many commercially important fish (e.g., barramundi), prawns, and mudcrabs.

In New Zealand, estuaries are the most heavily impacted of all coastal waters. Most are situated close to or within urban areas (Burns *et al.*, 1990). Most have been modified by reclamation or flood control works and have water-quality problems resulting from surrounding land use. Increasing coastal sedimentation is having a marked effect on many estuaries. This may increase with increased rainfall variability. In the South Island, increased coastal sedimentation has disrupted fish nursery grounds and destroyed weed beds, reef sponges, and kelp forests; in the North Island it has been linked to loss of seagrasses through worsening water clarity (RSNZ, 1993; Turner, 1995).

Over a long period, warming of the sea surface is expected (on average) to be associated with shoaling (thinning) of the mixing layer, lowering of phytoplankton growth-limiting dissolved inorganic nutrients in surface waters (Harris *et al.*, 1987; Hadfield and Sharples 1996), and biasing of the ecosystem toward microbial processes and lowered downward flux of organic carbon (Bradford-Grieve *et al.*, 1999). However, this would be modified regionally by any change in the Pacific Ocean to a more El Niño-like mean state. Warming also may lead to decreased storage of carbon in coastal ecosystems (Alongi *et al.*, 1998).

There is now palaeo-oceanographic evidence documenting environmental responses east of New Zealand to climatic warming, especially the Holocene "optimum" (~6–7 ka) and interglacial optimum (~120–125 ka), when SSTs were 1–2°C warmer than present. Immediately prior to and during those two periods, oceanic production appears to have increased, as manifested by greater amounts of calcareous nanoplankton and foraminifers (e.g., Lean and McCave, 1998; Weaver *et al.*, 1998). Other evidence suggests that storms in the New Zealand region may have been more frequent in warmer epochs (Eden and Page, 1998), affecting the influx of terrigenous material into the continental shelf (Foster and Carter, 1997). There also may be a relationship between strong El Niño events and the occurrence of toxic algal blooms in New Zealand waters (Chang *et al.*, 1998). Nevertheless, we do not know, over the longer term, how the oceanic biological system in the southwest Pacific will be influenced by the interaction of ENSO events with the overall warming trend.

South of the subtropical front, primary production is limited by iron availability (Boyd *et al.*, 1999), which has varied in the past. It is not known how or whether aeolian iron supply to the Southern Ocean in the southwest Pacific (Duce and Tindale, 1991) may be altered by climate change, although it could be affected by changes in aridity and thus vegetation cover over Australia as well as by strengthening of the westerlies. In any case, Harris *et al*. (1988) demonstrate that the strength of the zonal westerly winds is linked to recruitment of stocks of spiny lobsters over a wide area.

If reduction or cessation of North Atlantic or Antarctic bottomwater formation were to occur (Manabe and Stouffer, 1994; Hirst, 1999), this could lead to significant changes in deep ocean chemistry and dynamics, with wide ramifications for marine life. The common southern hemisphere copepod *Neocalanus tonsus* could be affected because it spends part of the year at depths between 500 and 1,300 m but migrates seasonally to surface waters, becoming the focus of feeding of animals such as sei whales and birds (Bradford-Grieve and Jillett, 1998).

The northern part of New Zealand is at the southern extension of the distribution of marine subtropical flora and fauna (Francis and Evans, 1993). With a warming climate, it is possible that many species would become a more permanent feature of the New Zealand flora and fauna and extend further south.

12.4.8. Landscape Management as a Goal for Conservation and Adaptation

Ecosystems that are used for food and fiber production form a mosaic in a landscape in which natural ecosystems also are represented. Aquatic systems, notably rivers and groundwater, often play a crucial role. Given the issues of fragmentation and salinization in many parts of the region, especially Australia, landscape management as an integrated approach (PMSEIC, 1999) may be one of the best ways of achieving conservation goals and human needs for food and fiber in the face of multiple stresses—of which climate change is only one.

This complex interconnection of issues in land management is evident in most parts of Australia and New Zealand—notably in the tropical coastal zone of Queensland, where rapid population and economic growth has to be managed alongside agricultural land use that impacts soil and riverine discharge into the waters of the GBR, a growing tourist industry, fisheries, indigenous people's rights, as well as the climatic hazards of tropical cyclones, floods, and droughts. Climate change and associated sea-level rise are just one of several major issues in this context that may be significant in adding stress to a complex system.

Similar complexities arise in managing other major areas such as the Murray-Darling basin, where control of land degradation through farm and plantation forestry is being considered as a major option, partly for its benefits in controlling salinization and waterlogging and possibly as a new economic option with the advent of incentives for carbon storage as a greenhouse mitigation measure. Similar problems and processes apply in New Zealand, where plantation forestry is regarded as a major option in land use and GHG mitigation.

12.5. Food and Fiber

12.5.1. Introduction

Some 60% of Australia is used for commercial agriculture (Pestana, 1993). Only 2% is used for broad acre and intensive crop production; 4% is sown to pastures. Soil and topography are major constraints on cropping, which produces about 50% of the gross value of farm production—the rest being divided equally between meat production and livestock products such as wool and milk.

Russell (1988) identifies climatic "frontiers" affected by climate change and interdecadal variability in rainfall—namely, the inland limit to agriculture (mean annual rainfall <300 mm in the south and <750 mm in the north), the southern limit of effective summer rainfall; and the lower rainfall limit of high value crops (on the order of 1,000 mm). Temperature also is limiting, with some temperate crops held south of their high-temperature (northern) limit, and other more tropical crops held at their low-temperature (southern or high-altitude) limit. Large areas of the interior and west are desert or very arid rangelands with low yields; much of this land is now returned to Aboriginal management.

There is great interannual variability, especially in the interior and more northern regions, associated mainly with ENSO, convective rainfall, and tropical cyclones. Australia is known as a land of droughts and flooding rains. Secondary factors such as wildfires also account for losses of fodder, animals, and farm infrastructure (sheds, fences, machinery), and hail causes significant crop losses. Accordingly, drought and disaster relief policies are matters of ongoing concern (O'Meagher *et al*., 1998, 2000; Pittock *et al*., 1999), as is sustainability in the face of economic pressures and global change (Abel *et al*., 1997).

In New Zealand, pastoral agriculture provides more than 40% of the country's export earnings (Statistics New Zealand, 1998). Dairy farming is the major activity in wetter areas; sheep dominate hilly and drier areas, and beef cattle are widely distributed throughout the country. Pastures are highly productive—composed largely of introduced grass and nitrogen-fixing legume species—and support high stock numbers. Rainfall in New Zealand generally is not strongly seasonal, but high evapotranspiration rates in the summer make pastoral agriculture in the east vulnerable to largely ENSO-related variability in summer rainfall.

12.5.2. Pastoral Farming

Howden *et al*. (1999d) have summarized and updated work by Hall *et al*. (1998), McKeon *et al*. (1998), and Howden *et al*. (1999a,b). They find that although CO_2 increase alone is likely to increase pasture growth, particularly in water-limited environments, there also is strong sensitivity to rainfall, so that a 10% reduction in rainfall would counter the effect of a doubled CO_2 concentration. A 20% reduction in rainfall at doubled CO_2 is likely to reduce pasture productivity by about 15% and live-weight gain in cattle by 12% and substantially increase variability in stocking rates, reducing farm income. The latest scenarios, which have substantial reduction in rainfall in many parts of Australia, would tend to reduce productivity.

Howden *et al.* (1999d) also found that doubled CO_2 concentrations are likely to increase the deep drainage component under pastures, which may increase the risk and rates of salinization where the potential for this problem exists. Doubled CO_2 and increased temperature would result in only limited changes in C_3 and C_4 grass distributions (Howden *et al*., 1999a).

In New Zealand, productivity of dairy farms might be adversely affected by a southward shift of undesirable subtropical grass species, such as *Paspalum dilatatum* (Campbell *et al*., 1996). At present, *P. dilatatum* is recognized as a significant component of dairy pastures in Northland, Auckland, Waikato, and the Bay of Plenty. A "user-defined" management threshold for the probability of finding this grass in dairy pasture is predicted by a climate profile technique (Campbell and Mitchell, 1996). This can be considered the point at which adaptive management changes are regarded as necessary. This technique was applied with the IS92a (mid) and IS92e (high) climate change scenarios and the CSIRO4 GCM pattern, using the CLIMPACTS integrated assessment model (Kenny *et al*., 1995, 2000). Results indicate a significant southward shift in the probability of occurrence of *P. dilatatum* with global warming; more southerly geographic thresholds are reached at later dates, but 25–30 years earlier with the higher emissions scenario.

Comprehensive assessment of the response of dairy cattle to heat stress in NSWand Queensland was carried out by Davison *et al.* (1996). Physiological effects of heat stress include reduced food intake, weight loss, decreased reproduction rates, reduction in milk yields, increased susceptibility to parasites, and, in extreme cases, collapse and death. Heat stress can be reduced by the use of shade and sprinklers, and thresholds for their use can be determined. Jones and Hennessy (2000) applied this adaptation to the Hunter Valley in NSW, using probabilistic estimates of temperature and dewpoint changes resulting from climate change for the IS92 range of scenarios to 2100. They then estimated the probabilities of given milk production losses as a function of time and calculated the economic benefits of provision of shade and sprinklers. They conclude that heat-stress management in the region would be cost-effective. However, such adaptation may not be as cost-effective in a hotter or more humid climate.

Howden and Turnpenny (1997) and Howden *et al.* (1999e) also have looked at heat stress in beef cattle. They find that heat stress already has increased significantly in subtropical Queensland over the past 40 years (where there has been a warming trend) and that it will increase further with greenhouse-induced global warming. They suggest a need for further selection for cattle lines with greater thermoregulatory control, but they point out that this may be difficult because it may not be consistent with high production potential (Finch *et al.*, 1982, 1984).

12.5.3. Cropping and Horticulture

Cropping in Australia recently has undergone great diversification, from predominantly wheat and barley to include a variety of other crops, including rice, cotton, pulses, and oilseeds. Cane sugar is grown extensively in coastal areas of Queensland. Many of these crops are subject to frost limitations on seasons and to water stress in dry spells; some are subject to direct heat stress or deterioration during heat waves. For example, wheat grain protein composition deteriorates after several days above 35°C (Burke *et al.*, 1988; Behl *et al.*, 1993), making it less suitable for high-value uses such as pasta and breadmaking. However, climate warming may allow earlier planting and faster phenological development, resulting in little change in heat shock risk up to a 4°C mean warming (Howden *et al.*, 1999c). Independently, increasing CO_2 can result in a decrease in wheat grain protein content—also leading to a decrease in breadmaking quality (Rogers *et al.*, 1998). A potential complication of these impacts is water stress that results in decreased yield and potentially increased protein.

Howden *et al.* (1999c) report a comprehensive study of global change impacts on Australian wheat cropping. Studies were conducted of changes in wheat yields, grain quality, and gross economic margins across 10 sites in the present Australian wheat belt. Results were scaled up to provide national estimates, with and without varying planting dates. Response surfaces were constructed across the full range of uncertainty in the CSIRO (1996a) scenarios and are shown in bar-graph form in Figure 12-3. The estimated increase in yield resulting from physiological effects of a doubling of actual atmospheric CO_2 is about 24%. The analysis assumes that the regional distribution of cropping is unaffected. (This is not completely accurate, but changes at the margins of present areas would not change the total yield much.) The best variety of wheat is used under each scenario, with current planting dates (a) and optimal planting dates (b) for each scenario. Note that yield reaches a maximum at about 1°C warming with current planting dates but about 2°C with optimal planting dates and that yield drops rapidly with decreases in rainfall. Under the SRES scenarios, warming in Australian wheat-growing areas would exceed 2°C and could be well in excess of 6°C by 2100; actual CO_2 concentrations could be between 540 and 970 ppm.

Doubling CO_2 alone produced national yield increases of 24% in currently cropped areas, but with a decline in grain nitrogen content of 9–15%, which would require increases in the use of nitrogen-based fertilizer of 40-220 kg ha^{-1} or increased rotations of nitrogen-fixing plants. Using the mid-range values from the CSIRO (1996a) scenario (which includes both slab-ocean and coupled GCMs and is now superseded—see below), climate change added to CO_2 increase led to national yield increases of 20% by 2100 under present planting practices or 26% with optimum planting dates (Howden *et al.*, 1999c). Regional changes varied widely.

Howden's response surfaces show that for doubled CO_2 but no change from historical rainfall, a 1°C increase in temperature would slightly increase national yield (see Figure 12-3a) when the best variety was used with the current planting window. However, the slope of the temperature curve turned negative

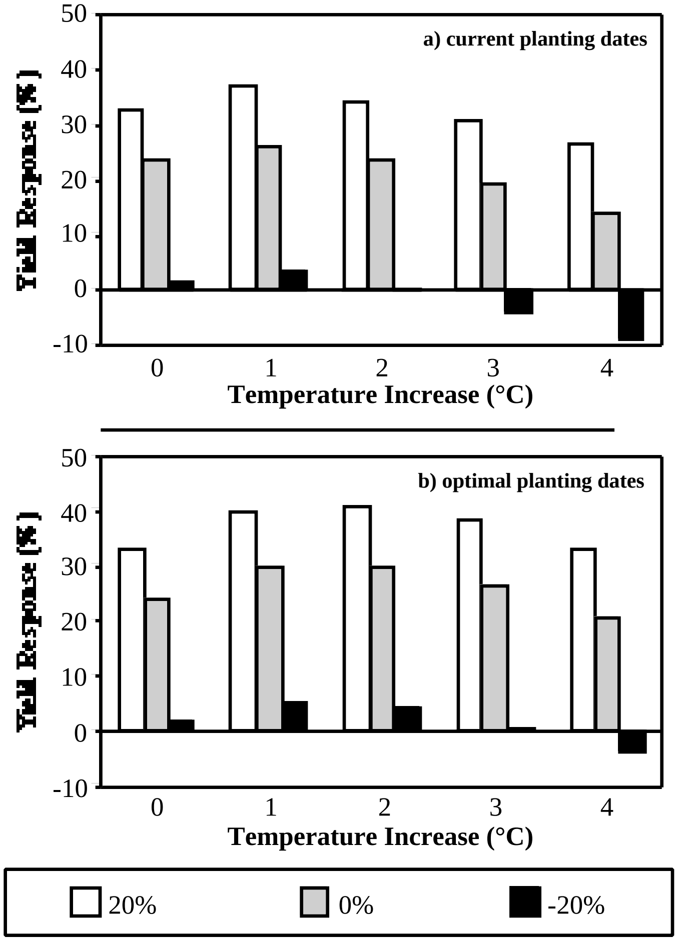

Figure 12-3: Percentage change in average annual total Australian wheat yield for doubling of actual CO_2 (to 700 ppm) and a range of changes in temperature and rainfall. Yield response is shown for rainfall changes of +20% (white), 0 (stippled), and -20% (black), for warmings of 0–4ºC.

beyond 1°C, so the yield at 2°C was predicted to be similar to that at present temperatures, and the total yield declined below the current value for greater warmings. Adoption of earlier planting windows with climate change extended the yield plateau to 2°C warming before the slope of the temperature curve became negative (see Figure 12-3b). This was based on the present regional distribution of cropping, although cropping could expand into drier marginal areas with higher CO_2—but this may be countered by substantial reductions in rainfall or land degradation in currently cropped areas. Yield decreases rapidly with decreases in rainfall.

These response surfaces were used by Howden *et al*. (1999d) with the SRES scenarios (see Section 12.1.5.4), which use only recent coupled-ocean GCMs that show reductions in rainfall over most of mainland Australia in summer and winter. Results indicate that for mid-range scenarios (A1-mid and B2-mid) extended to 2100, national yields are reduced 3% without adaptation compared with current yields and increase only 3% with adaptation. Yields decline in western Australia and south Australia but increase in the eastern states. With the A2-high scenario, there are much larger negative impacts, with cropping becoming nonviable over entire regions, especially in western Australia. These results highlight the importance of the more negative rainfall scenarios found with the coupled-ocean GCMs.

In New Zealand, generally drier conditions and reductions in groundwater will have substantial impacts on cereal production in Canterbury (east coast South Island), the major wheat and barley production area of New Zealand. Other grain-producing areas (primarily Manawatu and Southland) are less likely to be affected. Grain phenological responses to warming and increased CO_2 are mostly positive, making grain filling slightly earlier and decreasing drought risk (Pyke *et al*., 1998; Jamieson and Munro, 1999). Although grain-filling duration may be decreased by warmer temperatures, earlier flowering may compensate by shifting grain filling into an earlier, cooler period.

Maize production is mainly in Waikato (upper middle North Island) and Bay of Plenty and Poverty Bay (east coast North Island), with some production (more likely to be for silage than grain) further south in Manawatu and Canterbury. Rising temperatures make this crop less risky in the south, but water availability may become an issue in Canterbury.

Sweetcorn is grown mostly on the east coast of the North Island (Poverty Bay and Hawke's Bay) but increasingly in Canterbury. Climate warming is decreasing frost risk for late-sown crops, extending the season and moving the southern production margin further south. In the South Island, production is irrigated and is vulnerable to changes in river flows and underground water supply.

Horticulture in Australia includes cool,temperate fruit and vegetables in the south and at higher elevations, extensive areas of tropical fruits in the northeast and in irrigated areas in the northwest, and a rapidly expanding viticulture industry in cool and warm temperate zones. Many temperate fruits require winter chill or vernalization—which in some cases can be replaced by chemical treatments—and are strongly affected by disease and hail. Other more tropical fruit are subject to disease outbreaks and severe damage from hail, high winds, and heavy rain from tropical storms. These fruits are all likely to be affected by climate change, but few studies have been made (but see Hennessy and Clayton-Greene, 1995; Basher *et al.*, 1998).

In New Zealand, climate change may have mixed results on horticulture. Kiwifruit require some winter chill (Hall and McPherson, 1997a), and studies by Salinger and Kenny (1995) and Hall and McPherson (1997b) suggest that some varieties in some regions will become marginal; warmer summers and extended growing seasons may benefit others but may adversely affect timing for overseas markets.

Chilling requirements for most cultivars of pip-fruit are easily satisfied. However, some common cultivars have shown an adverse reaction to excessively warm conditions, with problems such as sunburn, water-core, and lack of color.

There has been a southern expansion of grapes in New Zealand over the past few decades, sometimes into more climatically marginal land. The New Zealand wine industry to date has shown a largely beneficial response to warm, dry conditions, which are expected to become more dominant in the east, but limitations on groundwater for irrigation may become a problem. Warmer conditions also are assisting expansion of the citrus industry in the north of New Zealand and are particularly beneficial for mandarins. However, this region would be susceptible to any increase in the location-specific frequency of subtropical storms reaching New Zealand.

12.5.4. Forestry

When Europeans arrived in Australia in 1788, there were approximately 70 Mha of forests. Since then, 40% has been cleared and a similar amount has been affected by logging; only about 25% remains relatively unaffected (Graetz *et al*., 1995; State of the Environment, 1996). Nationally, land clearing still exceeds planting, although this varies greatly across the states, and is occurring mainly in areas defined as woodlands. Plantations have been expanding in Australia at an increasing rate since 1990, currently by more than 50,000 ha yr^{-1} (National Greenhouse Gas Inventory, 2000). Much of this planting is occurring on farmed land and receives federal government support (Race and Curtis, 1997). Additional plantings are occurring to ameliorate land degradation problems such as erosion, waterlogging, and salinization, and further plantings are associated with the establishment of carbon sinks (Howden *et al*., 1999d).

Forests cover about 8.1 Mha (29%) of New Zealand's land area. Of this, about 6.4 Mha are in natural forest and 1.7 Mha in planted production forests. New forest establishment increased markedly during the 1990s. Almost all areas of harvested forest are replanted; during 1998, 52,000 ha of new forest plantings occurred (Statistics New Zealand, 1999).

Climatic factors are well known to influence species distributions (Hughes *et al.*, 1996; Austin *et al*., 1997) and productivity (Landsberg and Waring, 1997). CO_2 concentrations also have a direct effect (Curtis and Wang, 1998). Kirschbaum (1999a,b) has used a forest growth model to assess response to climate change and CO_2 increases for a site near Canberra.

Howden and Gorman (1999) review this and other work on the impact of global change on Australian temperate forests. Productivity of exotic softwood and native hardwood plantations is likely to be increased by CO_2 fertilization effects, although the amount of increase is limited by various acclimation processes and environmental feedbacks through nutrient cycling. Where trees are not water-limited, warming may expand the growing season in southern Australia, but increased fire hazard and pests may negate some gains. Reduced rainfall in more recent scenarios would have adverse effects on productivity and increase fire risk. Increased rainfall intensity would exacerbate soil erosion problems and pollution of streams during forestry operations. In *Pinus radiata* and Eucalyptus plantations, fertile sites are more likely to have increased productivity for moderate warmings, whereas infertile sites could have decreased production. To date, large uncertainties have lowered the priority of climate change in management considerations.

Despite large year-to-year climatic variability, many Australian native species are confined in their natural climatic range to within 1 or 2°C average mean temperature (Hughes *et al.*, 1996; Pouliquen-Young and Newman, 1999), so without human intervention their survival will be threatened by warmings outside these ranges (see Section 12.4.1).

Of New Zealand's 13 Mha of land used for pastoral farming, at current prices 3–5 Mha of hill country would yield higher returns under forestry. Such land is being converted to plantation forestry at a rate of 40,000 ha yr^{-1}, from an initial rate averaging 60,000 ha yr^{-1} over the past decade (Statistics New Zealand, 1998); the recent decrease in planting rate reflects current lower wood prices. Carbon trading would facilitate increased planting rates, possibly up to 90,000 ha yr^{-1} (MAF, 1999). Steep land is particularly uneconomic to manage for pastoral farming and could be converted to forest or scrubland by planting or abandonment and regrowth. Control of possums (a pest introduced from Australia by early European settlers) to minimize transfer of diseases to farm animals has the added benefit of improving the health and regenerative capacity of some indigenous forests (Ministry for the Environment, 1997).

Biomass from forest residues and purpose-grown crops already provides 6% of New Zealand's primary energy supply (EECA, 1996) and significant energy resources for Australia. Biomass use is expected to increase substantially over the next decade (Sims, 1999), partly as a response to constraints on net carbon emissions. This also may encourage increased forestry planting rates.

The direct effects of elevated CO_2 on yield from *radiata* pine plantations are expected to be small in New Zealand. However, regional uncertainties remain with regard to possible increased growth loss under warmer, wetter conditions as a result of existing and new pests and diseases and losses from wind and fire associated with extreme weather events. Biosecurity mechanisms are being improved in New Zealand and abroad to better manage risk. Long-term trends in forest nutritional status are being examined. Indicators of sustainable forestry practices are receiving increasing attention. Risks from fire and wind also are being investigated in New Zealand. Systems to measure and predict effects on carbon sequestration in plantation forests are being improved.

12.5.5. Fisheries

Australia specializes in high-value, low-tonnage fisheries such as lobsters, pearl oysters, prawns, abalone, and tuna. Totaling about AU$2 billion yr^{-1} (ABARE, 2000), these fisheries are a significant local primary industry. Tonnage produced is very small by world standards because Australian surface waters generally are low in nutrients as a result of prevailing winds and boundary currents (Kailola *et al.*, 1993). New Zealand's Exclusive Economic Zone (EEZ) is one of the largest in the world (Statistics New Zealand, 1999), and its NZ$1.23 billion export revenues from fisheries in 1998 constituted 5.5% of total export revenue for that year (Seafood New Zealand, 2000).

For both countries, relationships have been established between recruitment of some fish species and climate variations, suggesting that fisheries in the region will be sensitive to climate change. However, it is uncertain how local winds and boundary currents that advect larvae and affect upwelling of nutrients might respond to GHG-induced climate changes, and downscaling from relevant global climate change model fields has not yet been done. Hence, this section concentrates on reporting studies of observed sensitivities of fisheries in the Australasian region to climate variability. There is insufficient information to date to project the impact of climate change on fisheries productivity.

Understanding of existing processes suggests that if El Niño were to become a more prevalent condition, the Indonesian throughflow and the Leeuwin current (Meyers, 1996) could weaken. If winds were favorable for upwelling, the west coast of Australia could undergo a dramatic shift from a low-production, high-biodiversity ecosystem to a more productive ecosystem typical of temperate shelves.

Australia's single largest fishery is western rock lobster (AU$260 million yr^{-1}—ABARE 2000). Presently, settlement of larval lobsters (and adult catch rates some years later) is much higher in La Niña years (high coastal sea level, high SST, strong Leeuwin current) than in El Niño years (Pearce and Phillips, 1994). Because the mechanism appears to be through larval advection processes, however, it is unclear whether the species' spawning strategy would adapt to a sustained shift to a weaker Leeuwin current. Many other western Australian fisheries also correlate (some positively, some negatively) with ENSO (Caputi *et al.*, 1996), through unknown mechanisms. Whether these mechanisms would continue to operate under the combined influence of a sustained weaker Leeuwin current (which tends to reduce temperatures) and a worldwide rise in SST is unknown. Southern bluefin tuna spawn where the Indonesian throughflow enters the Indian Ocean, but the impact of a possibly reduced throughflow also is unknown.

Conditions on the south coast of Australia also are influenced—but to a lesser degree—by the Leeuwin current, which tends to keep near-surface nutrient levels low. In addition, winds are favorable to downwelling, except during some summers, when Australia's only example of strong classical wind-driven coastal upwelling occurs off Portland, Victoria. Small meridional shifts of the subtropical high-pressure ridge modulate summer upwelling. Ecosystem impacts of this are poorly known.

On the east coast of Australia, the East Australian Current (EAC) is a dominant influence on coastal marine ecosystems. The EAC enhances upwelling and primary production (Hallegraeff and Jeffrey, 1993) and presumably fisheries, although this has yet to be demonstrated apart from its effect on the distribution of several tuna species (Lyne *et al.*, 1999). Farther north, Vance *et al.* (1985) report a correlation of catches of banana (but not tiger) prawns with rainfall, probably as a result of runoff-driven export of juveniles from estuary nursery beds.

Post hoc analyses (Smith, 1996) of a dramatic decline in the late 1980s in the Australian gemfish fishery suggest a combination of fishery pressure and poor recruitments as the cause. Recruitment appears to correlate with climatic cycles (Thresher, 1994). Smith (1996) developed a quantitative framework to evaluate management strategies for this and other fisheries.

For New Zealand, there is some evidence that fisheries recruitment may be enhanced by more frequent ENSO events (Harris *et al.*, 1988), although possible negative effects of increased incidence of toxic algal blooms also have been observed (Chang *et al*., 1998). Changes in ENSO and ocean variability may combine with ocean warming in ways that are poorly understood. Recent New Zealand studies on snapper (Francis 1993, 1994a; Francis *et al.*, 1997), gemfish (Renwick *et al.*, 1998a), and hoki have shown that climatic variations may have a significant impact on spawning success or failure and subsequent recruitment into marine fish populations. Growth rates of juvenile and adult snapper appear to increase when SSTs are warmer (Francis, 1994b). This may have significant effects on the timing and scale of recruitment (e.g., Francis *et al.*, 1997). El Niño appears to have resulted in a westward shift of Chilean jack mackerel in the Pacific and subsequent invasion of this species into New Zealand waters in the mid-1980s (Elizarov *et al.*, 1993). This species now dominates the jack mackerel fishery in many areas. Variations in the abundance and distribution of pelagic large gamefish species in New Zealand may be closely correlated with variability in the ocean climate, with implications for recreational fishers as well as the tourist industry operating from charter boats.

Environmental temperature has a major influence on the population genetics of cold-blooded animals, selecting for temperature-sensitive alleles and genotypes. In New Zealand snapper, differences in allele frequencies at one enzyme marker have been found among year classes from warm and cold summers (Smith, 1979). Such differences could impact survival, growth rates, and reproductive success.

Finally, it should be noted that, if the wildcard of possible reduction or cessation of North Atlantic or Antarctic bottomwater formation were to occur (Manabe and Stouffer, 1994; Hirst, 1999), this could lead to significant changes in deep ocean chemistry, ocean dynamics, and nutrient levels on century time scales. This could have wide, but presently unknown, ramifications for fisheries in Australian and New Zealand waters.

12.5.6. Drought

In the Australia and New Zealand region, droughts are closely related to major drivers of year-to-year and decadal variability such as ENSO, Indian Ocean SSTs, the Antarctic Circumpolar Wave (White and Peterson, 1996; Cai *et al*., 1999; White and Cherry, 1999), and the Interdecadal Pacific Oscillation (Mantua *et al.*, 1997; Power *et al*., 1998; Salinger and Mullan, 1999), as well as more or less chaotic synoptic events. These are all likely to be affected by climate change (see Sections 12.1.5 and 12.2.3, and TAR WGI Chapters 9 and 10).

Using a transient simulation with the NCAR CCMO GCM at coarse resolution (R15) (Meehl and Washington, 1996), Kothavala (1999) found for northeastern and southeastern Australia that the Palmer Drought Severity Index indicated longer and more severe droughts in the transient simulation at about 2xCO_2 conditions than in the control simulation. This is consistent with a more El Niño-like average climate in the enhanced greenhouse simulation; it contrasts with a more ambivalent result by Whetton *et al*. (1993), who used results from several slab-ocean GCMs and a simple soil water balance model. Similar but less extreme results were found by Walsh *et al*. (2000) for estimates of meteorological drought in Queensland, based on simulations with the CSIRO RCM at 60-km resolution, nested in the CSIRO Mk2 GCM.

Aglobal study by Arnell (1999), using results from an ensemble of four enhanced greenhouse simulations with the HadCM2 GCM and one with HadCM3, show marked decreases in runoff over most of mainland Australia, including a range of decreases in runoff in the Murray-Darling basin in the southeast by the 2050s of about 12–35%. HadCM3 results show large decreases in maximum and minimum monthly runoff. This implies large increases in drought frequency.

The decrease in rainfall predicted for the east of New Zealand by downscaling from coupled AOGCM runs for 2080 and the corresponding increase in temperature are likely to lead to more drought in eastern regions, from East Cape down to Southern Canterbury. Eastern droughts also could be favored by any move of the tropical Pacific into a more El Niño-like mean state (see Table 3-10). The sensitivity of New Zealand agriculture and the economy to drought events was illustrated by the 1997–1998 El Niño drought, which was estimated to result in a loss of NZ$618 million (0.9%) in GDP that year. A drought in north and central Otago and dry conditions in Southland associated with the 1998–1999 La Niña resulted in a loss of about NZ$539 million in GDP (MAF, 2000).

Recurring interest in Australia in policies on drought and disaster relief is evidence of a problem in managing existing climate variability and attempts to adapt (O'Meagher *et al.,* 1998). Present variability causes fluctuations in Australian GDP on the order of 1–2% (White, 2000). Drought and disaster relief helps immediate victims and their survival as producers (e.g., QDPI, 1996) but does not reduce costs to the whole community and in fact may prolong unsuitable or maladapted practices (Smith *et al.,* 1992; Daly, 1994), especially if there is climatic change. Farm productivity models are being used to simulate past and present farm production and to assess causes of and management options for coping with drought (Donnelly *et al*., 1998). This is contributing to the fashioning of drought assistance and advisory policies.

The potential impact of drought on the Australian economy has declined, in relative economic terms, over time in parallel with the decline in the importance of agriculture to the economy (ABARE, 1997; Wilson and Johnson, 1997). In 1950–1951, the farm sector constituted 26.1% of GDP, whereas currently (1997–1998) it constitutes 2.5%. Similarly, the contribution of the farm sector to Australian exports has fallen from 85.3% (1950–1951) to 19.6% (1997–1998), with a reduction in the total farm sector labor force of about 6%. This despite the fact that farm production has increased over the same period. Thus, drought remains an important issue throughout Australia for social, political, geographical, and environmental reasons (Gibbs and Maher, 1967; West and Smith, 1996; Flood and Peacock, 1999).

Stehlik *et al.* (1999) studied the impact of the 1990 drought on more than 100 individuals from 56 properties in central Queensland and northern NSWto document the social experiences of dealing with drought. They conclude that there is strong evidence that the impact of the extended drought of the 1990s is such that rural Australia will never be the same again: "There is a decline in population: a closing down of small businesses, fewer and fewer opportunities for casual or itinerant work, more and more producers working 'off-farm'and a reduction in available services."

A change in climate toward drier conditions as a result of lower rainfall and higher evaporative demand would trigger more frequent or longer drought declarations under current Australian drought policy schemes, which rely on historical climate data and/or land-use practices on the basis of an expectation of historical climatic variability. A major issue for operational drought schemes is the choice of the most relevant historical period for the relative assessment of current conditions (Donnelly *et al*., 1998).

Examples of Australian government involvement in rural industries that have been subject to decline in commodity prices over several decades (e.g., wool) suggest that the industries will be supported until the cost to the overall community is too high and the long duration or high frequency of drought declarations is perceived as evidence that the drought policy is no longer appropriate (Mercer, 1991; Daly, 1994). In the case of wool, the shift of government policy from that of support to facilitation of restructuring has involved a judgment about future demand and therefore prices (McLachlan *et al*., 1999) and has only occurred after an extended period of low prices (Johnston *et al*., 1999). With a change in climate toward drier conditions, drought policy probably would follow a similar path.

The New Zealand Government response to drought comes under Adverse Climatic Events and Natural Disasters Relief policy that was released in 1995. Government responds only when rare climatic or natural disasters occur on a scale that will seriously impact the national or regional economy and the scale of the response required is beyond the capacity of local resources. The policy is to encourage industry/community/individual response, rather than reliance on government support.

Science has a major role in assessing the probability that recent and current climatic conditions could be the result of natural variability or increased GHGs. At best, these assessments are presented in probabilistic terms (e.g., Trenberth and Hoar, 1997). The public and its representatives will have to judge what constitutes evidence of anthropogenic effects and to what extent future projections and their impacts should be acted on. Because of their impact, future droughts provide a very public focus for assessing the issues of climate change compared to natural variability. Appropriate land-use and management practices can be reassessed by using agricultural system models with CO_2 and climate projections from GCMs (Hall *et al.,* 1998; Howden *et al.,* 1999f; Johnston *et al.,* 1999). However, political judgments between the alternatives of supporting existing land use or facilitating reconstruction are likely to require greater certainty with regard to the accuracy of GCMs than is currently available (Henderson-Sellers, 1993).

One source of adaptation is seasonal and long-lead climate forecasting. This is one area in which climate science already is contributing to better agricultural management, profitability, and, to some extent, adaptation to climate change (Hammer *et al.*, 1991, 2000; Stone and McKeon, 1992; Stone *et al*., 1996a; Johnston *et al.,* 1999). Indeed, empirical forecasting systems already are revealing the impact of global warming trends (Nicholls *et al.,* 1996b; Stone *et al.,* 1996b), and these systems already are adapting to climate change through regular revision and improvements in forecasting skill.

12.5.7. Pests and Diseases

Cropping, horticulture, and forestry in Australia and New Zealand are vulnerable to invasion by new pests and pathogens for which there are no local biological controls (Sutherst *et al*., 1996; Ministry for the Environment, 1997). The likelihood that such pests and pathogens—particularly those of tropical or semi-tropical origin—will become established, once introduced to New Zealand, may increase with climate warming.

Indepth case studies are being conducted in Australia to test the performance of pest impact assessment methodologies for estimating the vulnerability of local rural industries to pests under climate change (Sutherst *et al*., 1996). In New Zealand, pests that already are present may extend their ranges and cause more severe damage. For example, because of the reduced incidence of frosts in the north of New Zealand in recent years, the tropical grass webworm *(Herpetogramma licarisalis)* has increased in numbers and caused severe damage in some pastures in the far north.

The vulnerability of horticultural industries in Australia to the Queensland fruit fly *Bactrocera (Dacus) tryoni* under climate change was examined by Sutherst *et al*. (2000). Vulnerability was defined in terms of sensitivity and adaptation options. Regional estimates of fruit fly density, derived with the CLIMEX model, were fed into an economic model that took account of the costs of damage, management, regulation, and research. Sensitivity analyses were used to estimate potential future costs under climate change by recalculating costs with increases in temperature of 0.5, 1.0, and 2°C, assuming that the fruit fly will occur only in horticulture where there is sufficient rainfall or irrigation to allow the crop to grow. The most affected areas were the high-altitude apple-growing areas of southern Queensland and NSW and orange-growing areas in the Murrumbidgee Irrigation Area. Apples and pears in southern and central NSW also were affected. A belt from southern NSW across northern Victoria and into South Australia appeared to be the most vulnerable.

Adaptation options were investigated by considering, first, their sustainability under present conditions and, second, their robustness under climate variability and climate change. Bait spraying is ranked as the most sustainable, robust, and hence most promising adaptation option in boh the endemic and fruit fly exclusion zones, but it causes some public concern. The sterile insect technique is particularly safe, but there were concerns about costs, particularly with large infestations. Exclusion is a highly effective approach for minimizing the number of outbreaks of Queensland fruit fly in fly-free areas, although it is vulnerable to political pressure in relation to tourism. These three techniques have been given the highest priority.

12.5.8. Sustainability

Ecological and indeed economic sustainability has become a major issue in Australia and New Zealand (e.g., Moffatt, 1992). Australian government policy has been to integrate sustainability issues within a raft of polices and programs relating national heritage, land care, river care, wetlands, and carbon sequestration (Commonwealth of Australia, 1996). In both countries, land-use change and exotic pests and diseases, notably feral animals, are threatening many native species and ecosystems. In Australia, this is exacerbated by land degradation, notably soil erosion and increasing salinization brought about by loss of vegetative cover and rising water tables resulting from reduced evapotranspiration in catchments and irrigation with inadequate drainage.

These issues have been reviewed in several recent papers and reports, including a paper prepared for the Australian Prime Minister's Science, Engineering and Innovation Council (PMSEIC, 1999). This paper states that continuing degradation is costing Australia dearly in terms of lost production, increased costs of production and rehabilitation, possible damage to a market advantage as a producer of "clean and green" goods, increasing expenditures on building and repairing infrastructure, biodiversity losses, declining air and water quality, and declining aesthetic value of some landscapes.

PMSEIC (1999) states that the Australian community expects the use and management of resources to be economically, environmentally, and socially sustainable, which will require changes in management processes backed by science and engineering innovation. The report emphasizes that individual problems are linked and that an integrated approach is necessary to combat degradation and pursue remediation.

Climate change may exacerbate these problems by increasing opportunities for colonization by exotic species (e.g., woody weeds), by affecting the water balance and water tables, and by increasing erosion rates and flood flows through heavier rain events. Increased fire frequency also may threaten remnant forest and other ecosystems and impact soil degradation.

12.5.9. Global Markets

The impacts of climate change on food and fiber production in Australasia will be direct and indirect, the latter through changing global supply and demand influenced by climatic changes in other parts of the globe. Because a large proportion of food and fiber production in both countries is exported, the effect of commodity prices already is a major influence on the areas and mix of plantings and production, as well as profitability (Stafford Smith *et al*., 1999). Adaptation in both countries has taken the form of changes in the mix of production between, for example, wool, lamb and beef, dairy products, horticulture and viticulture, and, most recently, farm and plantation forestry, as well as increasing exports of value-added and processed products. Increased variability of production resulting from climate change may restrict expansion of such added-value products. Response to markets has led to rapid changes in some sectors, but this is more difficult for commodities that require longer investment cycles, such as viticulture and forestry. Nevertheless, adaptation to a highly variable environment is a feature of Australian agriculture, and adaptations to climate change also may contribute to exports of agricultural technology. Improved forecasts of commodity prices and longer term trends in supply and demand, taking into account seasonal climate and ENSO forecasts, are a major means of adaptation. This will be especially important for climate change impacts and will require understanding of global effects.

In New Zealand, there are implications for future wood flows of scenarios for rates of increased areas of forest plantations. Currently, of the 18 million m^3 log volume harvested annually in New Zealand, one-third is used for domestic consumption and two-thirds is exported. Using a 50,000 ha yr^{-1} planting rate, by 2010 the ratio is expected to be 20:80, and by 2025 it is expected to be 5:95. Clearly, there is a need for an export focus. If sufficiently large export markets do not materialize for New Zealand, a major alternative use of wood within New Zealand could be for energy, especially if the economics change as a result of external considerations.

12.5.10. Indigenous Resource Management

Recognition of indigenous land rights in both countries recently has caused a much greater proportion of both countries to come back under the management control of Aboriginal and Maori peoples (Coombs *et al*., 1990; Langton, 1997). In many situations, this has led to less intense economic exploitation, with more varied land use, (e.g., for low-intensity farming and pastoralism, combined with some horticulture, fishing, and ecotourism). Europeans in both countries have much to learn from traditional indigenous knowledge of land management, including the traditional custodianship ethic—particularly with regard to climatic fluctuations, extreme events, and sustainability. Indigenous knowledge may well lead to greater exploitation of indigenous species for nutritional and medicinal purposes. On the other hand, the indigenous people also have much to gain from greater economic and technical expertise related to markets and new technologies and products.

For example, Aboriginal traditional fire management regimes permitted reproduction of fire-dependent floral species and widespread savannas suitable for grazing. Through the creation of buffer zones, these regimes protected fire-intolerant communities such as monsoonal forests (Langton, 2000). Removal of Aboriginal groups into settlements led to areas where wildfires, fueled by accumulated biomass, cause extensive damage. Research in collaboration with traditional Aboriginal owners recently has played a key role in joint management of National Parks where customary Aboriginal burning is promoted to conserve biodiversity.

Andersen (1999) looks at the commonly accepted contrast between European ("scientific") and Aboriginal ("experiential") perspectives in fire management and concludes that in fact, European fire managers often lack clear land management goals and are no more "scientific" than Aboriginal fire managers. He argues that the task now is to introduce scientific goals into both European and Aboriginal fire management. This may be particularly applicable in adapting to changing vegetation patterns and increased fire danger in a changing climate.

12.6. Settlements and Industry

12.6.1 Infrastructure

Climate change will affect settlements and industry through changes in mean climate and changes in the frequency and intensity of extreme events. Obviously, changes in average climate affect design and performance, including variables such as heating and cooling demand, drainage, structural standards, and so forth. However, in many cases average climate is only a proxy for design standards that are developed to cope with extreme demands or stresses such as flooding rains, gale-force wind gusts, heat waves, and cold spells.

If the severity, frequency, or geographic spread of extreme events changes, the impact of such changes on infrastructure may be severe. For instance, movement of tropical cyclones further south into areas where infrastructure is not designed to cope with them would have significant consequences.

The rate and nature of degradation of infrastructure is directly related to climatic factors. Computer models to predict degradation as a function of location, materials, and design and construction factors have been developed (Cole *et al*., 1999a,b,c,d). Because buildings and infrastructure that are being constructed now will have projected lives until 2050, placement, design, and construction changes to guarantee this life against climate change are needed. Moreover, the effects of degradation and severe meteorological events may have an unfortunate synergy. Increase in the rate of degradation as a result of climate change may promote additional failures when a severe event occurs. If the intensity or geographical spread of severe events changes, this effect may be compounded.

In New Zealand, a Climate Change Sustainability Index (CCSI) developed by Robinson (1999) rates the impact of climate change on a house and the contribution to climate change of GHG emissions from the house. The index includes GHG emissions from heating and cooling, comfort, tropical cyclone risk, and coastal and inland flooding. Basically, the closer the house is to sea level and/or a river or waterway, the lower the CCSI. Higher temperatures and rainfalls in general will shorten the life span of many buildings.

The impact of extreme climatic events already is very costly in both countries. This has been documented for Australia in Pittock *et al*. (1999), where it is shown that major causes of damage are hail, floods, tropical cyclones, and wildfire. In New Zealand, floods and landslides are the most costly climatically induced events, with strong winds and hail also important. The International Federation of Red Cross and Red Crescent Societies (1999) report estimates damages from a combination of drought, flood, and high wind (including cyclones, storms, and tornadoes) in Oceania (Australia, New Zealand, and the Pacific islands) to be about US$870 million yr^{-1} over the years 1988–1997. This figure apparently does not include hail damage, which is a major cost. Insured losses from a single severe hailstorm that struck Sydney in April 1999 were estimated at about AU$1.5 billion (roughly US$1 billion) (NHRC, 1999).

A scoping study for Queensland Transport (Queensland Transport *et al*., 1999) has identified vulnerabilities for the Queensland transport infrastructure that will require adaptation. Infrastructure considered include coastal highways and railways, port installations and operations (as a result of high winds, sea-level rise, and storm surges), inland railways and roads (washouts and high temperatures), and some airports in low-lying areas. Key climate variables considered were extreme rainfall, winds, temperatures, storm surge, flood frequency and severity, sea waves, and sea level. Three weather systems combining extremes of several of these variables—tropical cyclones, east coast lows, and tropical depressions—also were assessed.

Regional projections for each of these variables were created, with levels of confidence, for four regions of Queensland for 2030, 2070, and 2100. Overall, the potential effects of climate change were assessed as noticeable by 2030 and likely to pose significant risks to transport infrastructure by 2070, if no adaptation were undertaken. Setting new standards, in the form of new design criteria and carrying out specific assessments in prioritized areas where infrastructure is vulnerable, was recommended for roads and rail under threat of flooding, bridges, and ports. Detailed risk assessments for airports in low-lying coastal locations were recommended.

Many ports and coastal communities already suffer from occasional storm-surge flooding and wave damage. A series of studies identifies particular vulnerabilities in some Queensland coastal cities (Smith and Greenaway, 1994; AGSO, 1999). Inland and coastal communities also are vulnerable to riverine flooding (Smith *et al*., 1997; Smith, 1998a). Akey feature of these studies is the nonlinear nature of damage response curves to increased magnitude and frequency of extreme events. This is partly because of exceedance of present design standards and the generally nonlinear nature of the damage/stress relationship, with the onset of building collapse and chain events from flying or floating debris (Smith, 1998a).

A study by McInnes *et al*. (2000; see also Walsh *et al*., 2000) estimates the height of storm tides at the city of Cairns, in northern Queensland, for the present climate and for an enhanced greenhouse climate in which—based on the findings of Walsh and Ryan (2000)—the central pressure of tropical cyclones was lowered by about 10 hPa and the standard deviation of central pressure (a measure of variability) was increased by 5 hPa but the numbers were unchanged. Cairns is a low-lying city and tourist center, with a population of about 100,000 that is growing at about 3% yr^{-1}. Under present conditions, McInnes *et al*. (2000) found that the 1-in-100-year event is about 2.3 m in height; under the enhanced greenhouse conditions, it would increase to about 2.6 m, and with an additional 10- to 40-cm sea-level rise, the 1-in-100-year event would be about 2.7–3.0 m (see Figure 12-4). This would imply greatly increased inundation and wave damage in such an event, suggesting a possible need for changes in zoning, building regulations, and evacuation procedures.

Urban areas also are vulnerable to riverine flooding (Smith, 1998a) and flash floods exacerbated by fast runoff from paved and roofed areas (Abbs and Trinidad, 1996). Considerable effort has gone into methods to improve estimates of extreme

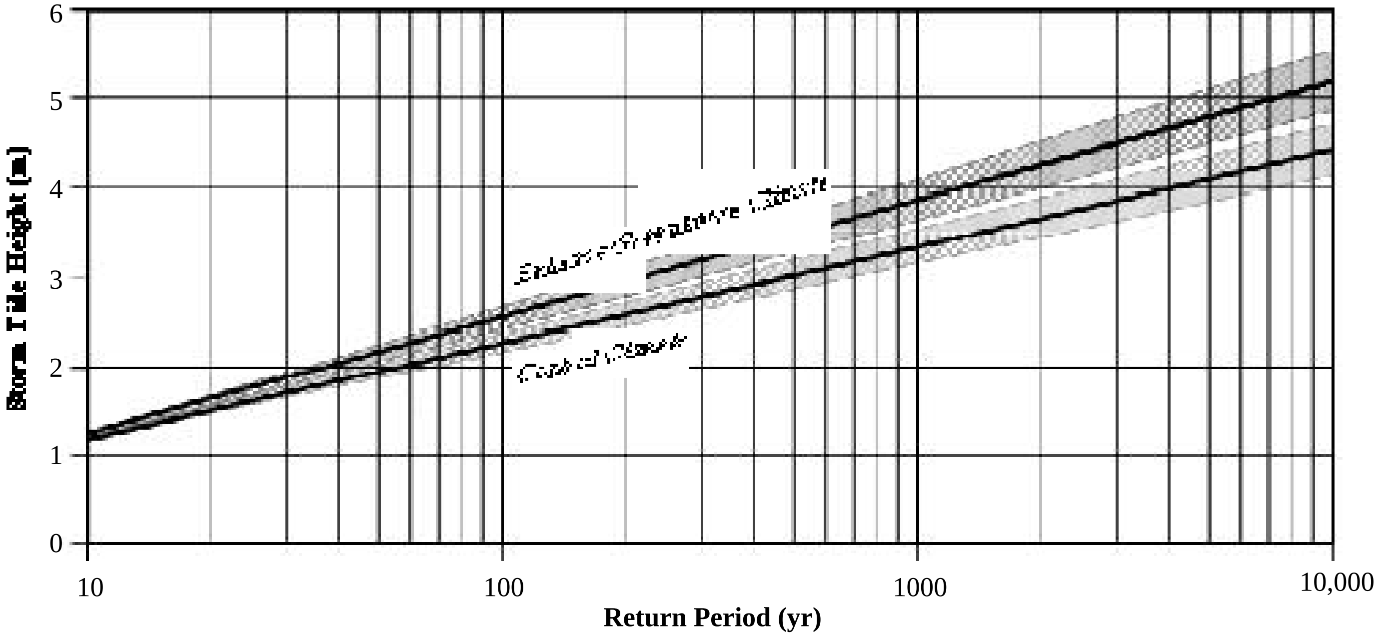

Figure 12-4: Simulated return periods (average time between events) of storm tides in Cairns, Queensland, for present climate (lower curve), and for enhanced greenhouse climate (upper curve), assuming 10 hPa lowering of central pressures and increased variability (additional 5 hPa standard deviation) of tropical cyclones. Anticipated mean sea-level rise should be added to these estimates. Uncertainty ranges of simulations are shown via grey shading (Walsh *et al*., 2000).

precipitation under present conditions (Abbs and Ryan, 1997; Abbs, 1998). Schreider *et al*. (2000) applied a rainfall-runoff model to three different catchments upstream of Sydney and Canberra under doubled-CO_2 conditions. They found increases in the magnitude and frequency of flood events, but these effects differed widely between catchments because of the different physical characteristics of each catchment.

The safety of publicly owned and private dams also is a major issue (ANCOLD, 1986; Webster and Wark, 1987; Pisaniello and McKay, 1998) that is likely to be exacerbated by increases in rainfall intensity and probable maximum precipitation (Pearce and Kennedy, 1993; Fowler and Hennessy, 1995; Abbs and Ryan, 1997; Hennessy *et al*., 1997).

Vulnerability depends not only on the severity of the potential impacts but on hazard mitigation measures put in place (including time- and location-specific hazard prediction), crisis management capability, and policies that avoid or minimize the hazard. These matters are discussed in Smith (1998a), Handmer (1997), and Kouzmin and Korac-Kakabadse (1999).

12.6.2. Investment and Insurance

According to Pittock *et al*. (1999), based on Insurance Council of Australia figures, major climatic catastrophe insurance losses from 1970 through 1996 averaged AU\$208 million yr^{-1}. Of these losses, nearly half were from tropical cyclones; one-quarter were from hail. Other flooding and storm damage accounted for most of the rest; losses from fire were less than 10% of the total. Figures provided by the Insurance Council of New Zealand show that insurance industry payouts for New Zealand climatic catastrophes averaged NZ\$23.5 million yr^{-1} (inflation-adjusted) between 1980 and 1998.

In an Australian study of insurance and climate change, Leigh *et al*. (1998a) examined four major climatic disasters: the Brisbane floods of 1974, the South Australian bushfires of 1983, the Nyngan floods of 1990, and the New South Wales bushfires of 1994. Total estimated damage from these four events was AU\$178 million, \$200–400 million, \$47 million, and \$168 million, respectively; however, the insurance industry bore only 39, 31, 9, and 33% of the cost, respectively. Government relief assistance was roughly equal to that from the insurance industry, and about 70–90% of that was provided by the federal government.

Leigh *et al.* (1998b) have reported on the potential for adaptation to climate change by the insurance industry in Australia by setting out an array of reactive and proactive options. Responses include reducing insurers' exposure or controlling claims through risk management to encourage disaster mitigation measures. The latter has the advantage of reducing overall losses to the community, rather than merely redistributing them among stakeholders. Natural disaster insurance can be more selective, so that good risks are rewarded and poor risks are penalized. Such rate-based incentives can motivate stakeholders to plan to more effectively minimize exposure to disasters. However, some individuals and businesses may have difficulties if some previously insurable properties become uninsurable against flood because of an increase in location-specific flood frequency. Government intervention and possible co-insurance between government and insurers also were canvassed. Cooperation between insurers and governments to ensure development and enforcement of more appropriate building codes and zoning regulations was regarded as desirable.

12.6.3. Energy and Minerals

Energy demand, essentially for air conditioning, is likely to increase in the summer and in more tropical parts of Australia and New Zealand (Lowe, 1988). However, winter demand for heating will similarly decrease in the winter and in cooler areas. Thus, increasing population in tropical and subtropical parts of Australia may combine with climate change to increase overall energy demand.

The other major uses of energy in Australia are transport and manufacturing. Transport demand generally will increase because of population growth but may be significantly affected by the changing distribution of growth across the continent, which in turn may be affected by climate change.

In general, warming will slightly reduce energy efficiency in most manufacturing, including electricity generation, but this is relatively minor compared with possible technological improvements in efficiency. Any decrease in water supply (see Section 12.3.1), such as is expected in the Murray-Darling basin in Australia, would impact adversely on hydroelectric generation and cooling of power stations, especially where there already is competition between water uses. Fitzharris and Garr (1996) predict benefits for hydroelectricity schemes in New Zealand's Southern Alps because they expect less water will be trapped as snow in the winter, which is the time of peak energy demand for heating.

12.6.4. Coastal Development and Management, Tourism

Economic development is proceeding rapidly in many coastal and tropical areas of Australia and New Zealand. This is fueled partly by general economic and population growth, but it is amplified in these regions by resource availability, shipping access for exports, attractive climates and landscapes, and the growth of the tourism industry. This selective growth in investment is leading to greater community risk and insurance exposure to present and future hazards, while many classes of hazard are expected to increase with global warming (see Table 3-10). Thus, present development trends are likely to make the impacts of climate change worse, especially for sea-level rise and increasing intensity of tropical cyclones. Particular attention should be paid to the implications for the risk to life and property of developments in coastal regions, as well as ways to reduce vulnerability to these hazards. Possible adaptations include improved design standards, zoning, early warning systems, evacuation plans, and emergency services.

Management of waste and pollution from settlements and industry will become more critical because of the potential for flood and waste discharge to impinge on water quality, including inland and coastal algal blooms, as well as adverse effects on ecotourism associated with damage to coral reefs (see Section 12.4.7). Sediment and pollution fluxes into the GBR lagoon already are a major concern (Larcombe *et al*., 1996). This could be exacerbated by greater flood flows (see Sections 12.1.5.3 and 12.6.1) and increasing population and development. Higher temperatures will accentuate algal blooms.

The other major tourism and recreation sector that is likely to be seriously affected by climate change is the ski industry, which will be faced with significant reductions in natural snow cover (see Sections 12.2 and 12.4.4) and limited acceptance of artificial snow (Konig, 1998). Also, as the potential ranges of certain agricultural pests such as the fruit fly (see Section 12.5.7) and disease vectors such as mosquitos (see Section 12.7.1) increase, possible transfer of such pests and diseases through tourism may become an increasing issue.

12.6.5. Risk Management

As a result of the large uncertainties associated with possible future climate, as well as the stochastic nature of extreme events, there is great need for a risk management approach to development planning and engineering standards. In accordance with the precautionary principle, uncertainty should not be allowed to stand in the way of risk reduction measures, which in any case often will have other benefits such as protection of coastal and riverine environments.

Australia and New Zealand have jointly developed a risk management standard (Standards Australia and Standards New Zealand, 1999) that is designed to provide a consistent vocabulary and assist risk managers by delineating risk management as a four-step process that involves risk identification, risk analysis, risk evaluation, and risk treatment. Beer and Ziolkowski (1995) specifically examined environmental risk management and produced a risk management framework.

Examples of the application of a risk analysis approach are given in Sections 12.5.2 for pastures in New Zealand, 12.6.1 for storm surges, and 12.8.4 for irrigation water demand.

12.7. Human Health

12.7.1. Diseases and Injuries

Impacts of climate and climate change on health can be direct or indirect. Direct effects that are readily attributed to climate include heat stress and the consequences of natural disasters. However, the resulting burden of disease and injury may be less than that from indirect effects such as disrupted agriculture and reduced food security. Positive and negative effects can be anticipated, but there is insufficient evidence to state confidently what the balance will be (see Chapter 9). We have not attempted to estimate the overall economic costs of climate change impacts on health in the Australia-New Zealand region because there is considerable debate about the derivation and interpretation of monetary costs (see Chapter 19).

Guest *et al.* (1999) compared heat-related deaths in the five major Australian cities in the period 1977–1990 with those expected under different climate change scenarios (CSIRO, 1996a) for the year 2030. They estimate that greenhouse-induced climate change would increase climate-related deaths in the summer by a small amount, but this would be more than balanced by a reduction in climate-related deaths in the winter. Overall, this resulted in a decrease of 8–12% in climate-attributable mortality under the CSIRO “high” scenario compared to a scenario with no climate changes (but expected population changes).

The only study in New Zealand to date of elevated temperatures and mortality was conducted by Hales *et al.* (2000). Daily numbers of deaths in Christchurch were compared with measures of weather and ambient particulate pollution from June 1988 to October 1993. Above the third quartile (20.5°C) of summer maximum temperatures, an increase of 1°C was associated with a 1.3% increase (95% confidence interval, 0.4–2.3%) in all-cause mortality and a slightly greater increase in mortality from respiratory conditions. There was no evidence of interaction between the effects of temperature and particulate air pollution. Greater than expected numbers of deaths also occurred during winter days of low temperature, although this was not statistically significant. This suggests that cold-related deaths will be less common in a warmer climate. However, the mechanisms that explain excess winter mortality are not well understood.

The effects of solar ultraviolet (UV) radiation on skin cancer, skin aging, and cataracts of the eye are particularly important in New Zealand and Australia, which already have the highest skin cancer rates in the world (Marks *et al*., 1989). The etiology of skin cancer is not fully understood, and factors other than sun exposure undoubtedly are involved. However, UV-B is a key factor. Present levels of UV radiation in this region are relatively high and have been increasing in the past 20 years (McKenzie *et al.*, 1999). It is expected with a high degree of confidence that if UV flux at ground level increases at a faster rate as a result of greenhouse-related cooling in the upper stratosphere and subsequent slowdown in the breakdown of ozone-depleting substances, the incidence of melanomas and other skin cancers will increase (Armstrong, 1994; Longstreth *et al*, 1998). Australians and New Zealanders of pale-skinned European descent will be particularly vulnerable to these effects. This topic is discussed in more detail in Chapter 9.

The numbers of notified cases of arbovirus infections (illnesses caused by insect-borne viruses) have increased in Australia in recent years (Russell, 1998), and exotic insect species such as *Aedes albopictus* and *Aedes camptorhynchus* that are competent vectors of viruses such as dengue and Ross River virus have been detected at New Zealand borders (Hearnden *et al.*, 1999).

There is good evidence that the frequency of mosquito-borne infections in this region is sensitive to short-term variations in climate. For example, outbreaks of Ross River fever and Murray Valley encephalitis in southeast Australia tend to follow heavy rainfall upstream in the Murray-Darling catchment (Nicholls, 1993; Maelzer *et al*., 1999). In other parts of Australia where the predominant vector is the coastal mosquito *A. camptorhynchus*, variations in sea level also contribute to outbreaks of illness from Ross River virus (Mackenzie *et al.*, 1994). No quantitative estimates have been made of the possible impact of long-term climate change on rates of vector-borne infections. However, present climate change scenarios suggest that parts of Australia and New Zealand will experience conditions that are more favorable to breeding and development of mosquitoes (Bryan *et al*, 1996). In these areas, warmer conditions will tend to extend the range of reservoir hosts, decrease the extrinsic incubation period of arboviruses, and encourage outdoor exposure of humans (Weinstein, 1997). Therefore, it is expected with a high degree of confidence that the potential for insect-borne illness will increase. Whether this potential is translated into actual occurrence of disease will depend on many other factors, including border security, surveillance, vector eradication programs, and effectiveness of primary health care.

Endemic malaria was present in North Queensland and the Northern Territory until early in the 20th century (Ford, 1950; Black, 1972). Vectors to transmit the disease still are present in that part of Australia, and climate change will favor the spread of these mosquitoes southward (Bryan *et al*., 1996). The disease-limiting factor at present is the effectiveness of local health services that ensure that parasitemic individuals are treated and removed from contact with mosquitoes. Therefore, climate change on its own is unlikely to cause the disease to return to Australia, unless services are overwhelmed. In New Zealand there currently are no mosquitoes that are capable of transmitting malaria; even under global warming scenarios, the possibility of an exotic vector becoming established is considered to be slight (Boyd and Weinstein, 1996).

Studies of the prevalence of asthma in New Zealand have shown an association with average temperature (Hales *et al.*, 1998). Electorates with lower mean temperatures tend to have lower levels of asthma, after adjusting for confounding factors. The reason is not clear but may be related to exposure to insect allergens. If this were so, warming may tend to increase the frequency of asthma, but too little is known about the causes of the disease to forecast the impact of climate change on asthma in Australia and New Zealand.

Climate change may influence the levels of several outdoor air pollutants. Ozone and other photochemical oxidants are a concern in several major Australian cities and in Auckland, New Zealand (Woodward *et al.*, 1995). In Brisbane, Australia, current levels of ozone and particulates have been associated with increased hospital admission rates (Petroeschevsky *et al.*, 1999) and daily mortality in persons ages 65 and over (Simpson *et al*., 1999). Outdoor particulate pollution in the winter (largely generated by household fires) has been associated with increased daily mortality in Christchurch, New Zealand (Hales *et al*., 2000). Formation of photochemical smog is promoted in warmer conditions, although there are many other climatic factors—such as windspeed and cloud cover—that are at least as important as temperature but more difficult to anticipate. A rise in overnight minimum temperatures may reduce the use of fires and hence emissions of particulates, but it is not known how this might affect pollution and population exposures.

Toxic algal blooms may affect humans as a result of direct contact and indirectly through consumption of contaminated fish and other seafood. At present this is not a major public health threat in Australia or New Zealand, but it is an economic issue (because of effects on livestock and shellfish). It could affect very large numbers of people (Oshima *et al.*, 1987; Sim and Wilson, 1997). No work has been carried out in Australia or New Zealand relating the health effects of algal blooms to climate. Elsewhere in the Pacific, it has been reported that the incidence of fish poisoning (resulting from ingestion of fish contaminated with ciguatoxins) is associated with ocean warming in some eastern islands, but not elsewhere (Hales *et al.*, 1999). It is uncertain whether these conditions will become more common in Australia and New Zealand with projected climate change.

Since 1800, deaths specifically ascribed to climatic hazards have averaged about 50 yr^{-1} in Australia (Pittock *et al*., 1999), of which 40% are estimated to be caused by heat waves and 20% each from tropical cyclones and floods. Although this is not necessarily representative of present conditions because of changing population, statistical accounting, and technologies, it is an order of magnitude estimate. This suggests that if heat waves, floods, storm surges, and tropical cyclones do become more intense, some commensurate increase in deaths and injuries is possible. Whether this will occur will depend on the adequacy of hazard warnings and prevention. Statistics from other developed countries with larger populations indicate a recent trend toward increasing damages but decreasing death and injury from climatic hazards. Thus, hazard mitigation is possible, although it must more than outweigh increased exposure resulting from larger populations in hazardous areas.

12.7.2. Vulnerability

Climate impacts are determined not just by the magnitude of environmental change but also by the vulnerability of exposed populations. Examples of biophysical vulnerability are the susceptibility of pale-skinned populations to the effects of UV radiation and the vulnerability of isolated island ecosystems such as New Zealand's to invasion by exotic species (including disease vectors). Another example is infections spread to humans from animals, such as cryptosporidiosis. New Zealand has relatively high rates of notified cases of this infection (Russell *et al.*, 1998). This may be related to the conjunction of high densities of livestock and unprotected human drinking water supplies. In such a setting, increased rainfall intensity would promote transmission of the pathogen (by washing animal excreta containing the organism into the water supply).

Woodward *et al.* (1998) reviewed social determinants of vulnerability to health effects of climate change in the Pacific region. Australia and New Zealand are two of the wealthiest countries in the region, with relatively low population densities and well-developed social services. For these reasons, Australia and New Zealand are likely to be less vulnerable overall to many of the threats to health from climate change than neighboring countries. However, within both countries there are groups that are particularly susceptible to poor health. Sources of disadvantage include poverty, low housing standards, high-risk water supplies, lack of accessible health care, and lack of mobility. These factors tend to be concentrated in particular geographical locations and ethnic groups (Crampton and Davis, 1998) and carry with them increased vulnerability to most of the hazards that are associated with climate variability and climate change.

There have been no studies in New Zealand or Australia that have attempted to quantify vulnerability to disease and injury. Some work has been carried out on indices of environmental vulnerability (e.g., Kaly *et al*., 1999). These studies have focused on measures of the resilience and integrity of ecosystems; with further development, they may assist in future forecasts of the impacts of climate change on human health.

12.7.3. Complexities of Forecasting Health Effects

There is no opportunity to study directly, in a conventional controlled fashion, the effects on health of climate change. Research to date in Australia and New Zealand has concentrated on the association of climate variability, at relatively restricted spatial and temporal scales, with the incidence of disease. It is not simple to extrapolate from these findings to long-term climate change. This problem is not particular to Australia and New Zealand, but there are informative local examples in the literature. These include analyses of roles of climate-related variables other than temperature (e.g., the critical effects of wind on air pollution, rainfall density on mosquito breeding, and humidity on heat stress); interactions with local ecosystems (e.g., the potential for amplification of certain arboviruses in New Zealand wildlife); and human behaviors that influence exposures (such as changing patterns of skin protection and the implications for UVexposures) (Hill *et al*, 1993; Russell, 1998b).

12.7.4. Public Health Infrastructure

A major challenge in Australia and New Zealand is how to protect and improve public health systems that deal with threats to health such as those that will potentially accompany climate change. Examples include border controls to prevent introduction of pathogens (including those from livestock and animal imports), measures required to ensure safe food and clean water, and primary health care services that reach the most disadvantaged and vulnerable members of the community. Threats to these systems include restrictions on government spending, increasing demands, and fragmented systems of purchase and provision of services.

With vector-borne diseases, the major challenge in Australia will be to control the expansion and spread of diseases that already are present in the country, such as Ross River virus and Murray Valley encephalitis—which are strongly influenced by climatic events. Introduction of new pathogens from close neighbors such as Papua New Guinea also is possible. Imported Japanese encephalitis and malaria remain serious threats, influenced principally by the numbers of people moving across the Torres Strait and the effectiveness of health services in the far north of Australia.

In New Zealand, the key issue for the health sector is how to prevent the introduction of vector-borne disease, particularly arboviruses carried by mosquitoes. Competent vectors for conditions such as Ross River virus and dengue have been detected frequently at entry points in recent years. This is likely to be a result of increasing trade and passenger traffic between New Zealand and other countries, as well as heightened awareness and better reporting. Eradication programs are expensive, and they are feasible only when the spread of exotic mosquitoes is confined. With repeated incursions and/or dispersion, the emphasis is likely to shift to control strategies.

12.7.5. Design of Human Environments

Several measures can be taken to better design human environments to cope with potential health stresses resulting from climate change. These measures include:

- Air conditioning and other measures to reduce exposure to heat
- Limiting exposure to disease vectors by measures such as use of screens on doors and windows and restriction of vector habitats (especially near waterways and urban wetlands)
- Land-use planning to minimize ecological factors that increase vulnerability to potential climate changes, such as deforestation, which increases runoff and the risk of flood-related injury and contamination of water supplies; animal stock pressures on water catchments; and settlement of marginal or hazardous areas such as semi-tropical coastal areas that are prone to storms and close to good vector breeding sites.

12.7.6. Vulnerable Populations, including Indigenous and Poor

Woodward *et al*. (1998) have argued that the effects of climate change on health will be most severe in populations that already are marginal. For these populations, climate change and sea-level rise impacts will be one more cause for “overload.” In general, indigenous people in Australia and New Zealand are vulnerable to the effects of climate change because they tend to be excluded from mainstream economic activity and modern technological education and experience higher levels of poverty, lower rates of employment, and higher rates of incarceration than the overall population. These factors have widespread and long-term impacts on health (Braaf, 1999).

For example, Northern Territory health data for 1992–1994 show that the mortality rate for indigenous people was 3.5–4 times greater than that for nonindigenous people. Life expectation at birth was 14–20 years lower for indigenous Australians than for nonindigenous Australians (Anderson *et al.*, 1996). The indigenous population displays diseases and health problems that are typical of developed and developing nations. This includes high rates of circulatory diseases, obesity, and diabetes, as well as diarrheal diseases and meningococcal infections. High rates of chronic and infectious diseases affect individual and community well-being and reduce resilience to new health risks (Braaf, 1999).

A changing climate has implications for vector-borne and waterborne diseases in indigenous communities. In the “Top End” of the Northern Territory during the wet season, hot and humid conditions are conducive for vectors of infectious diseases endemic in the region. Vectors include flies, ticks, cockroaches, mites, and mosquitoes. Flies can spread scabies and other diseases. Mosquitoes are vectors for Australian encephalitis and endemic polyarthritis. Giardia and shigella are water-borne diseases that are common among indigenous children in the region. Both can be spread from infected people to others through consumption of infected food and untreated water. Existing and worsening overcrowded housing conditions, poor sanitation, and poor housing materials create breeding grounds for infection. Climate changes and sea-level rise—which create conditions that are suitable for new vectors (such as malaria) or expand distributions of existing vectors—may expose such vulnerable populations to increased risks.

In New Zealand, the gap between the health of indigenous people and the remainder of the population is less marked than in Australia but is substantial nevertheless. In 1996, life expectancy at birth was 8.1 years less for Maori females than for non-Maori females and 9.0 years less for Maori males than for non-Maori males (Statistics New Zealand, 1998a). As in Australia, this difference is associated with and partly caused by poorer economic circumstances and lack of appropriate, effective services (Durie, 1994). Consequently, Maori are at greater risk of health problems related to climate variability and climate change. An example is the lack of reticulated water supplies in the East Cape of the North Island, an area in which the population is predominantly Maori and in many cases cannot afford to truck in water in times of drought.

Impact assessments that consider only biophysical relationships between climate and health will be inadequate in evaluating indigenous health outcomes. The possibility—or, indeed, likelihood—that people may have very different views concerning what makes them vulnerable to climate change, which impacts may be significant, and what responses may be implemented also will need to be considered (Braaf, 1999).

The present social circumstances of indigenous peoples provide a poor basis on which to build adaptation responses to climate change threats. Thus, policies that aim to improve resilience to climate change impacts could encompass efforts to reduce relevant social liabilities—poverty, poor education, unemployment, and incarceration—and support mechanisms that maintain cultural integrity. Adaptive strategies could pursue economic development of these communities while sustaining the environments on which these populations are dependent (Howitt, 1993).

In other parts of the Pacific, there are many countries that are particularly susceptible to the effects of climate change—especially low-lying island states, which are likely to be severely affected by sea-level rise and increases in storm activity. Australia and New Zealand have close relations with many of the Pacific island states. For example, New Zealand has particular responsibilities for Niue, the Cook Islands, and Tokelau and contains substantial expatriate communities from most of the islands. Climate-related threats to these islands (see Chapter 17) would impact immediately on Australia and New Zealand.

12.8. Adaptation Potential and Vulnerability

12.8.1. Adaptation and Possible Benefits of Climate Change

It has not been assumed that all the impacts of climate change will be detrimental. Indeed, several studies have looked at possible benefits. Moreover, adaptation is a means of maximizing such gains as well as minimizing potential losses.

However, it must be said that potential gains have not been well documented, in part because of lack of stakeholder concern in such cases and consequent lack of special funding. Examples that have not been fully documented include the possible spread of tropical and subtropical horticulture further poleward (but see some New Zealand studies, on kiwi fruit, for example—Salinger and Kenny, 1995; Hall and McPherson, 1997b). In southern parts of Australia and New Zealand, notably Tasmania, there could be gains for the wine industry, increased comfort indices and thus tourism, and in some scenarios increased water for hydroelectric power generation.

Guest *et al*. (1999) have documented possible decreases in winter human mortality alongside possible increased summer mortality (see Section 12.7.1), and Howden *et al*. (1999d) have shown that Australian wheat yields may increase for 1 or 2°C warming, before showing declines at greater warmings (see Section 12.5.3 and Figure 12-3). A similar situation may apply to forestry (see Section 12.5.4). Such studies take account of gains from increased CO_2 concentrations. Changes in overseas production and thus in markets in some cases also could lead to greater demand and higher prices for Australian and New Zealand primary products (see Section 12.5.9), but only if such changes do not disrupt world trade in other ways (e.g., lower capacity to pay).

Vulnerability and adaptation to climate change must be considered in the context of the entire ecological and socioeconomic environment in which they will take place. Indeed, adaptations will be viable only if they have net social and economic benefits and are taken up by stakeholders. Adaptations should take account of any negative side effects, which would not only detract from their purpose but might lead to opposition to their implementation (PMSEIC, 1999).

Adaptation is the primary means for maximizing gains and minimizing losses. This is why it is important to include adaptation in impact and vulnerability studies, as well as in policy options. As discussed in Chapter 18, adaptation is necessary to help cope with inevitable climate change, but it has limits; therefore, it would be unwise to rely solely on adaptation to solve the climate change problem.

In some cases adaptation may have co-benefits. For example, reforestation to lower water tables and dryland salinization or to reduce storm runoff may provide additional income and help with mitigation (reduction of GHG emissions). However, other potential adaptations may be unattractive for other reasons (e.g., increased setbacks of development in coastal and riverine environments). These considerations have particular application in Australia and New Zealand. Studies of adaptation to climate change in Australia and New Zealand are still relatively few and far between. They are summarized in the remainder of this section.

12.8.2. Integrated Assessments and Thresholds

Over the past decade there have been several national and regional assessments of the possible impacts of climate change. A regional assessment for the Macquarie River basin was done by Hassall and Associates *et al.* (1998, reported in Basher *et al.*, 1998); Howden *et al*. (1999d) made a national assessment for terrestrial ecosystems (see Section 12.5). Two other preliminary regional assessments cover the Hunter Valley in NSW (Hennessy and Jones, 1999) and the Australian Capital Territory (Baker *et al*., 2000). The former was based on a stakeholder assessment of climate change impacts that identified heat stress in dairy cattle as a subject for a demonstration risk assessment. Thresholds for heat stress and the probability of their being exceeded were evaluated, as were the economic value of adaptation through installation of shade and sprinklers (see Section 12.5.2; Jones and Hennessy, 2000). Baker *et al*. (2000) made a preliminary qualitative assessment of the impacts of scenarios on the basis of the CSIRO RCM at 60-km resolution (Hennessy *et al.*, 1998) on a wide range of sectors and activities.

However, most integrated studies in Australia and New Zealand have been "one-off" assessments, have lacked a time dimension, cannot readily be repeated to take account of advances in climate change science, and often have not placed the problem in its socioeconomic context. Several groups are collaborating on integrated modeling systems that overcome these drawbacks. In New Zealand this is called CLIMPACTS (Kenny *et al*., 1995; Warrick *et al*., 1996; Kenny *et al*., 1999, 2000), and an Australian system called OZCLIM has been based on it. These integrated models contain a climate change scenario generator, climate and land surface data, and sectoral impact models. They provide a capacity for time-dependent analyses, a flexible scenario approach, a capability for rapid updating of scenarios; and inclusion of models for different sectors. One application is reported in Section 12.5.2.

OZCLIM contains regional climate patterns for monthly temperature and rainfall over Australia from several GCMs and the CSIRO RCM. They can be forced or scaled by the latest emission scenarios, and variables include potential evapotranspiration and relative humidity. It is being adapted to produce projected ranges of impact variables and to assess the risk of exceeding critical thresholds (CSIRO, 1996b; Jones, 2000; Pittock and Jones, 2000).

There are different levels and styles of integration in impact and adaptation assessment, and several of these have been attempted in Australia and New Zealand. Bottom-up integration was done for a range of climate change scenarios in the water supply, pasture, crop, and environmental flow sectors for the Macquarie River basin study by Hassall and Associates *et al*. (1998). It also has been done in a more probabilistic way to take account of uncertainty, with a focus on the probability of exceeding a user-defined threshold for performance and the need for adaptation (Jones, 2000).

Top-down integration has been attempted via the use of global impacts assessment models with some regional disaggregation—such as a regional analysis based on the Carnegie Mellon University ICAM model, which was used to examine adaptation strategies for the Australian agricultural sector (Graetz *et al*., 1997). The principal conclusions were that climate matters and that the best strategy is to adapt better to climate variability.

Another top-down approach, based on an Australian regionalization of the DICE model of Nordhaus (1994), is that of Islam (1995). An initial application of this model to quantifying the economic impact of climate change damages on the Australian economy gave only a small estimate, but the authors expressed reservations about model assumptions and the need to better quantify climate impacts (Islam *et al.*, 1997). Others have examined the structure and behavior of the Integrated Model to Assess the Greenhouse Effect (IMAGE) but to date have not applied this to climate change impacts in Australia (Zapert *et al*., 1998; Campolongo and Braddock, 1999).

A spatially explicit modeling system known as INSIGHT is being developed to evaluate a wide range of economic, social, environmental, and land-use impacts that could affect large areas (Walker *et al*., 1996). It can map and summarize key social, economic, and environmental outcomes in annual steps to the year 2020. The need for such a system was identified through workshops involving potential stakeholders, and the system could factor in scenarios resulting from climate change.

As pointed out in PMSEIC (1999), much of Australia is subject to multiple environmental problems, of which climate change is only one. This leads to a logical emphasis on regional integrated assessments, which look for adaptations and policies that help to ameliorate more than one problem and have economic benefits.

12.8.3. Natural Systems

A large fraction of the region is composed of unmodified or nonintensively managed ecosystems where adaptation will depend mostly on natural processes. Vulnerability will occur when the magnitude or rate of climate variations lies outside the range of past variations. In some cases, adaptation processes may be very accommodating, whereas in others adaptation may be very limited. Ecosystems in the region handle a wide variety of climatic variability, in some cases with very large swings, but generally this variation occurs on short time scales—up to a few years. This does not necessarily confer adaptability to long-term changes of similar magnitude.

An important vulnerability identified by Basher *et al.* (1998) is the problem of temperatures in low to mid-latitudes that reach levels never before experienced and exceed the available tolerances of plants and animals, with no options for migration. The southwest of western Australia is a case in point (see Section 12.4.2). Another potential vulnerability arises from changes in the frequency of events. Examples include a climatic swing of duration exceeding a reproductive requirement (e.g., water birds in ephemeral lakes—Hassall and Associates *et al*., 1998) and damaging events occurring too frequently to allow young organisms to mature and ecosystems to become reestablished.

Vulnerability also is expected to exist where species or ecosystems already are stressed or marginal, such as with threatened species; remnant vegetation; significantly modified systems; ecosystems already invaded by exotic organisms; and areas where physical characteristics set constraints, such as atolls, low-lying islands, and mountain tops. Coral reefs, for instance, may be able to survive short periods of rising sea level in clear water but are less likely to do so in turbid or polluted water or if their growth rates are reduced by acidification of the ocean (Pittock, 1999). Vulnerability of coastal freshwater wetlands in northern Australia to salinization resulting from increasing sea level and the inability of some of these wetlands to migrate upstream because of physical barriers in the landscape is described in Sections 12.4.5 and 12.4.7.

Unfortunately, there is relatively little specific information about the long-term capacity for and rates of adaptation of ecosystems in Australia and New Zealand that can be used to predict likely outcomes for the region. Therefore, a large degree of uncertainty inevitably exists about the future of the region's natural ecosystems under climate change.

12.8.4. Managed Systems

In the region's agriculture, many farming systems respond rapidly to external changes in markets and technology, through changes in cultivars, crops, or farm systems. Mid-latitude regions with adequate water supplies have many options available for adaptation to climate change, in terms of crop types and animal production systems drawn from other climatic zones. However, at low latitudes, where temperatures increasingly will lie outside past bounds, there will be no pool of new plant or animal options to draw from, and the productivity of available systems is likely to decline.

Adaptation options will be more limited where a climatic element is marginal, such as low rainfall, or where physical circumstances dictate, such as restricted soil types. Even where adaptations are possible, they may be feasible only in response to short-term or small variations. At some point, a need may arise for major and costly reconfiguration, such as a shift from or to irrigation or in farming activity. Indeed, one adaptation process already being implemented in Australia to cope with existing competition for water is water pricing and trading, which is likely to lead to considerable restructuring of rural industries (see Section 12.4.6).

Management of climate variability in Australia currently involves government subsidies in the form of drought or flood relief when a specific level of extreme that is classified as exceptional occurs (Stafford Smith and McKeon, 1998; see also Section 12.5.6). An adaptive measure being applied in Australia and New Zealand is to improve seasonal forecasting and to help farmers optimize their management strategies (Stone and McKeon, 1992; Stone *et al*., 1996a; White, 2000), including reducing farm inputs in potentially poor years.

However, if a trend toward more frequent extremes were to occur, such measures might not allow farmers to make viable long-term incomes because there may be fewer good years. The question arises whether this is merely a string of coincidental extremes, for which assistance is appropriate, or whether it is part of an ongoing trend resulting from climate change. The alternative policy response to the latter possibility may well be to contribute to restructuring of the industry.

The PMSEIC (1999) report notes that there are opportunities for new sustainable production systems that simultaneously contribute to mitigation objectives through retention of vegetation and introduction of deeper rooted perennial pasture. Tree farming in the context of a carbon-trading scheme would provide additional opportunities, and this strategy could be linked to sustainability and alleviation of dryland salinity.

Nevertheless, the report recognizes that totally new production systems may be required for sustainability. These systems will need to capture water and nutrients that otherwise would pass the root zone and cause degradation problems. The design of such systems will entail research into rotating and mixing configurations of plants; manipulating phenology; modifying current crops and pastures through plant breeding, including molecular genetics; and possibly commercializing wildlife species and endemic biological resources. The report concedes, however, that there probably still will be agricultural areas where attempts to restore environmental and economic health will meet with little success.

Vulnerability and the potential for adaptation can be investigated quantitatively if a system and the climate change impacts on that system can be modeled. This was done by Pittock and Jones (2000) and Jones (2000) for climatically induced changes in irrigation water demand on a farm in northern Victoria. Here a window of opportunity is opened for adaptation via identification of a future time when adaptation would be necessary to reduce the risk of demand exceeding irrigation supply.

Jones (2000) used a model that was based on historical irrigation practice. Seasonal water use was used to estimate an annual farm cap of 12 Ml ha^{-1}, based on the annual allocated water right. Water demand in excess of this farm cap in 50% of the years was taken to represent a critical threshold beyond which the farmer cannot adapt. Conditional probabilities within projected ranges of regional rainfall and temperature change were utilized, combined with a sensitivity analysis, to construct risk response surfaces (see Figure 12-5). Monte Carlo sampling was used to calculate the probability of the annual farm cap being exceeded across ranges of temperature and rainfall change projected at intervals from 2000 to 2100. Some degree of adaptation was indicated as desirable by 2030, although the theoretical critical threshold was not approached until 2050, becoming probable by 2090 (see Figure 12-6).

In a full analysis, this example would need to be combined with an analysis of the likelihood of changes in water supply (e.g., Schreider *et al*., 1997) affecting the allocated irrigation cap and an evaluation of possible adaptation measures.

12.8.5. Human Environments

The most vulnerable human environments in Australia and New Zealand are those that are subject to potential coastal or riverine flooding, landslides, or tropical cyclones and other intense storms. Adaptation to natural variability in these cases usually takes the form of planning zones, such as setbacks from coasts and flood levels of particular return periods or engineering standards for buildings and infrastructure. Many of these settlements and structures have long lifetimes—comparable to that of anthropogenic climate change. This means that many planning zones and design standards may become inappropriate in a changing climate.

Adaptation in these circumstances depends on costs and benefits, the lifetime of the structures, and the acceptability of redesigned measures or structures (e.g., seawalls). Thus, responses will depend in part on aesthetic and economic considerations; poorer communities, such as many indigenous settlements, will be particularly vulnerable. Conflicts will arise between investors with short time horizons and local government or other bodies who think on longer time scales and may bear responsibility for planning or emergency measures. Complex jurisdictional arrangements often will add to the difficulties of adopting rational adaptation measures (Waterman, 1996).

In an attempt to meet these problems for the Australian coastline, a guide has been developed for response to rising seas and climate change (May *et al*., 1998), as well as good practice and coastal engineering guidelines (Institution of Engineers, 1998; RAPI, 1998).

Local governments in some parts of Australia and New Zealand are identifying measures they could implement to adapt to climate change. For example, the Wellington Regional Council is required by its Regional Policy Statement to periodically

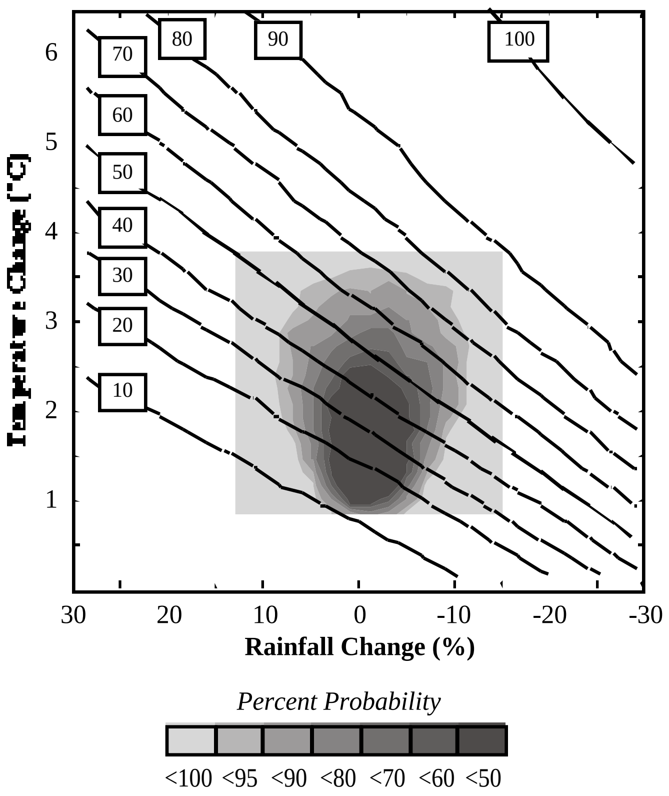

Figure 12-5: Risk response surface incorporating cumulative probability plots (in shaded box) for climate change magnitudes as indicated on x- and y-axes. Indicated percentage probabilities are probabilities of climate change in northern Victoria in 2070 lying within each shaded area (thus, there is a 100% probability of climate within the shaded square, and a 50% probability of climate within the innermost region). Probability (in percent) of irrigation water demand exceeding farm supply cap in any one year, for indicated climate change, is indicated by oblique lines. Critical threshold (heavy line) is set at a 50% chance of exceeding the cap (Jones, 2000).

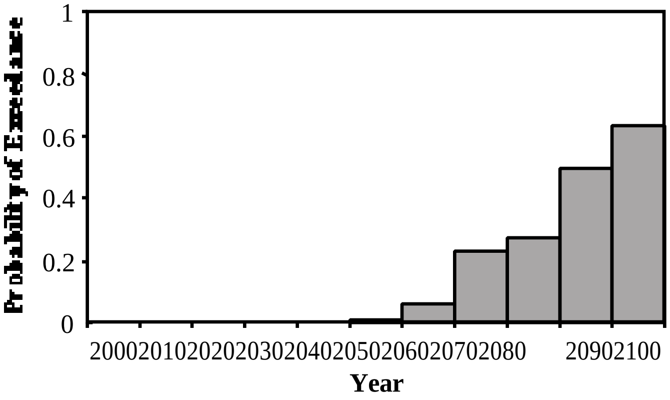

Figure 12-6: Change in probability of exceeding critical threshold (exceeding farm cap in 50% of all years) over time. Note that if farm cap were reduced through reductions in irrigation supply under climate change, the probability of the cap being exceeded would be increased (Jones, 2000).

review current knowledge on climate change and possible effects on natural hazards; the Council already allows for climate-induced variability in its flood protection activities (Green, 1999).

The region's health infrastructure is quite strong, and numerous existing adaptations, such as quarantine and eradication of disease vectors, are available to deal with the main changes expected. However, there is concern that already disadvantaged communities, especially indigenous people, may not have equitable access to adaptation measures. Another issue is the question of adaptations to deal with a climatic impact that may cause secondary effects. Examples include adaptations that require more energy production or higher water use, and vector controls that result in reduced population immunity to the disease carried.

12.8.6. Indigenous People

Traditional indigenous societies in the region have lived in a close and conscious relationship with their environment (Tunks, 1997; Skertchly and Skertchly, 2000). Australian Aborigines have modified and managed the landscape through the controlled use of low-intensity fire (Kohen, 1995). They have lived in Australia for at least 40,000 years. Thus, they have a long history of adaptation to sea-level rise, which rose by 130 m from the last glacial maximum 18,000 years ago until the present level was reached 6,000 years ago. Memories of these traumatic events are found in oral traditions recorded by early European settlers (Mulvaney and Kamminga, 1999).

With the recognition of indigenous land rights, indigenous people in both countries are now major land managers (Coombs *et al.*, 1990; Langton, 1997) and hence are impacted by and responsible for managing climatic impacts. The importance of their participation in the development of policy and response strategies to climate change is discussed in New Zealand Climate Change Programme (1990) and Tunks (1997), but to date their involvement has been minimal. This is a result partly of greater emphasis in Australia and elsewhere on mitigation of climate change rather than adaptation (Cohen, 1997), lack of indigenous community involvement in climate change research, and the array of other more pressing social issues for such communities (Braaf, 1999).

12.8.7. Extra-Regional Factors

Basher *et al*. (1998) draw attention to the vulnerability of the region to external influences arising from climate change—in particular, from likely changes in terms of trade (see also Stafford Smith *et al*., 1999). Increased risk of invasion by exotic pests, weeds, and diseases and possible immigration from neighboring territories rendered uninhabitable by rising sea level are other factors. These issues exist independent of climate change but are likely to be exacerbated by climate change. A variety of adaptations to deal with each problem exist and can be strengthened, but the costs involved and remaining impacts could be considerable.

12.9. Synthesis

12.9.1 Introduction

Many activities and ecosystems in Australia and New Zealand are sensitive to climate change, with positive and negative effects. Much climate sensitivity information is still qualitative, and there are substantial uncertainties in predictions of regional- to local-scale climate changes—especially rainfall changes and changes in extreme events. Thus, comprehensive, quantitatively based cross-sectoral estimates of net Australasian costs of climate change impacts are not yet available. Confidence remains very low in the impact estimate for Australia and New Zealand of –1.2 to –3.8% of GDP for an equivalent doubling of CO_2 concentrations (Basher *et al*., 1998). This estimate is based on climate change scenarios that are now outdated; does not include some potentially important impacts, including changes in weeds, pests and diseases, storm surges, and urban flooding; and does not account for possible adaptations to climate change.

Despite the uncertainties, there is a large body of knowledge and more agreement on changes than often is realized (e.g., between different coupled ocean-atmosphere climate models on the sign of the change in rainfall over large areas of Australia; see Section 12.1.5.1). There also is qualitative agreement on reduced water supplies in large agricultural regions of Australia (see Sections 12.3.1 and 12.5.6).

Potential net impacts on grazing, crops, and forests critically depend on the balance between the competing effects of warmings, positive or negative rainfall changes, direct physiological effects of higher CO_2 concentrations, and spatial and temporal variations in soil fertility. We expect with medium to high confidence that beneficial physiological effects of higher CO_2 concentration will become less dominant with time and effects of warming will become more damaging, especially given the expected tendency toward greater aridity over much of Australia. Impacts (and thus climate change benefits or damages) will not scale linearly with increasing GHG concentrations.

The following subsections draw together material from this chapter that is pertinent to the "policy-relevant questions" identified by the IPCC Bureau, as well as regional policy concerns.

12.9.2. Observed Consequences of Past and Current Climate Variability in the Region

Regional consequences documented in this chapter from floods, droughts, and temperature changes associated with recent ENSO events include losses in the pastoral agriculture sector from droughts (Australia, 1–2% of GDP; New Zealand, NZ$422 million estimated farm-gate costs from 1997 to 1999) and impacts on streamflow, water supply, stream ecology, horticulture, some commercial fisheries, and toxic algal blooms. Parts of the GBR have suffered mass coral bleaching from high SSTs (possibly related to ENSO and recent warming trends) and/or lowered salinity as a result of floods. Storms in the New Zealand region may have been more frequent in past warm epochs, leading to a greater influx of terrigenous material onto the continental shelf. Oceanic productivity east of New Zealand apparently increased immediately prior to and during warm periods 6,000–7,000 years ago and 120,000–125,000 years ago.

Extreme climatic events resulting from natural climatic variability in the past century have caused major damage and loss of life in Australia and New Zealand (see Sections 12.1.5.3 and 12.6.2). These extremes are expected to change in intensity, location-specific frequency, and sequence as a result of climate change (see Table 3-10 and Section 12.1.5.3), with major impacts on infrastructure and society unless strong adaptation measures are adopted.

12.9.3. Factors Influencing Vulnerability

12.9.3.1. Abrupt or Nonlinear Changes in Impacts

Several potential abrupt or nonlinear responses to climate change are listed in Table 12-1. In some cases, they involve a reversal of the sign of the effect with greater climate change; in others they result from the onset or acceleration of a biophysical or socioeconomic process that occurs or greatly accelerates beyond some threshold of climate change. Such thresholds can be quite location- and system-specific and need to be identified in collaboration between climatologists and stakeholders. The

Table 12-1*: Nonlinear or rapid climate change responses identified in this chapter.*

System	Description of Change	Certainty and Timing	Section
Great Barrier Reef	Reef death or damage from coral bleaching	Medium to high, next 20–50 years	12.4.7
Deep ocean	Chemical, dynamical, and biological changes from reduction in bottomwater formation	Low to medium, century time scale	12.4.7
Southwest of western Australia	Rapid loss of species with narrow annual mean temperature ranges	High, next 20–50 years	12.4.2
Australian alpine ecosystems	Loss of species as a result of warming and reduced snow cover	Medium to high, next 50 years	12.4.4
Insect-borne disease spread	Conditions more favorable to mosquitoes and other disease vectors	High potential, growing vulnerability	12.7.1
Agriculture	Shift from net profit to loss as a result of increased frequency of bad years	High potential in some places, next 20–50 years	12.8.4
Agriculture	Shift from positive to negative balance between benefits of increased CO_2 and losses from increasing aridity	High potential in parts of Australia, 50–100 years	12.5.2, 12.5.3
Built infrastructure	Change in magnitude and frequency of extremes to exceed design criteria, leading to rapid increases in potential damages to existing infrastructure	Medium to high in tropical coastal and riverine situations, next 30–50 years	12.6.1

frequency with which thresholds are exceeded often is used in engineering in the form of design criteria to withstand an event with a certain "return period," or average time between occurrences. It also can manifest itself as a change from an average profit to an average loss for a given enterprise such as a farm.

12.9.3.2. Interactions with Other Environmental and Social Factors

Some of the region's ecosystems are extremely vulnerable to invasion by exotic animal and plant species because of relative isolation before European settlement. Land-use changes have left some systems and areas more vulnerable to added stresses from climate changes, as a result of salinization or erosion, and because of ecosystem fragmentation, which lessens adaptation options for movement of species threatened by changing habitats (see Section 12.4.8).

Increasing human populations and development in coastal areas and on floodplains cause increasing vulnerability to tropical cyclones, storm surges, and riverine flooding episodes (see Sections 12.4.7 and 12.6.4), which may become more frequent with climatic change. Development has reduced the area and water quality of many estuaries, increasing the vulnerability of their ecosystems to sea-level rise and climate changes. Pressures on coral reefs including the GBR include increased coastal development, fisheries, tourism, and runoff of nutrients, chemicals, and sediment from land, as well as climate-related stresses such as rising sea level, rising temperatures, changes in tropical storm frequency, and acidification of the ocean from increasing CO_2 concentrations (see Section 12.4.7).

Poorer communities, including many indigenous settlements, are more vulnerable to climate-related natural hazards and stresses on health (see Section 12.7.6) because they often are in exposed areas and have less adequate housing, health, and other resources for adaptation.

Capacity to adapt is a function not only of the magnitude and critical nature of the climatic change but also of the demographics, economy, institutional capacity, and technology of a society. Thus, alternative socioeconomic futures will lead to different capacities to adapt. This has hardly been explored to date in Australia and New Zealand in relation to climate change.

12.9.3.3. Regional-Global Interactions

Reliance on exports of agricultural and forest products makes the region sensitive to changes in commodity prices produced by changes in climate elsewhere (see Section 12.5.9) and to increases in global forests as a result of carbon sink policies. Other extra-regional factors include increased risks of invasion by exotic pests, weeds, and diseases; pressures from immigration from neighboring low-lying Pacific island territories impacted by sea-level rise (see Section 12.7.6); and international agreements that constrain net emissions of GHGs. In an era of increasing globalization, these issues may assume more importance, although this report hardly touches on them.

12.9.4. Impacts for Differing Emissions Scenarios and Stabilization Pathways

Quantitative cross-sectoral impact assessments for differing scenarios are not yet available for Australia and New Zealand. Regional impacts will vary nonlinearly with time before and after stabilization of GHG concentrations. Warming will continue to increase after stabilization, but the beneficial effects of CO_2 on plants will no longer increase. Moreover, regional patterns of rainfall change, particularly in southern Australian and New Zealand areas, will tend to reverse after stabilization of GHGs (see Section 12.1.5.1). These complexities, together with the continuing post-stabilization rise in sea level, mean that estimated impacts at the time of stabilization may not be sufficient to determine whether the level of stabilization is a safe one.

12.9.5. Uncertainties and Risk Management

Given that some of the climate sensitivities listed in Section 12.9.6, and especially in Table 12-2, already have been observed for natural climate variations (such as El Niño), confidence is high that a range of impacts will occur in Australia and New Zealand as a result of climate change over the coming decades. This level of certainty, and the possibility that the early stages of greenhouse-related changes already may be occurring, justify prudent risk management through initiation of appropriate mitigation and adaptation strategies. Probabilistic assessments of risk, which account for the uncertainties, are regarded as a way forward. These assessments attempt to quantify the various sources of uncertainty to provide a conditional probability of climate change that would cause critical system performance thresholds to be exceeded and require adaptation or result in losses. Stakeholders may define their own subjective levels of acceptable risk and plan accordingly to adapt before or when the threshold is exceeded. Some examples for Australia and New Zealand are presented in this chapter (see Sections 12.5.2, 12.6.1, 12.8.2, and 12.8.4), but more are needed.

12.9.6. Vulnerability and Adaptability in Australia and New Zealand

The key regional concerns identified in this chapter regarding vulnerability to climate change impacts are ecosystem uniqueness, isolation, and vulnerability; agricultural commodities and terms of trade; droughts, floods, and water supply; increased coastal and tropical exposure to climate hazards; impacts on indigenous peoples and their involvement in adaptation planning; coral reefs; and Australian alpine areas.

Major expected impacts, vulnerability, and adaptability are summarized in Table 12-2. Note that although Australian and

***Table 12-2**: Main areas of vulnerability and adaptability to climate change impacts in Australia and New Zealand. Degree of confidence that tabulated impacts will occur is indicated by a letter in the second column (VH = very high, H = high, M = medium, L = low, VL = very low). These confidence levels, and the assessments of vulnerability and adaptability, are based on information reviewed in this chapter and assume continuation of present population and investment growth patterns.*

Sector	Impact	Vulnerability	Adaptation	Adaptability	Section
Hydrology and water supply	– Irrigation and metropolitan supply constraints, increased salinization—**H**	High in some areas	– Planning, water allocation, and pricing	Medium	12.3.1, 12.3.2
	– Saltwater intrusion into some island and coastal aquifers—**H**	High in limited areas	– Alternative water supplies, retreat	Low	12.3.3
Terrestrial ecosystems	– Increased salinization of dryland farms and some streams (Australia)—**M**	High	– Changes in land-use practices	Low	12.3.3
	– Biodiversity loss, notably in fragmented regions, Australian alpine areas, and southwest of WA—**H**	Medium to high in some areas	– Landscape management; little possible in alpine areas	Medium to low	12.4.2, 12.4.4, 12.4.8
	– Increased risk of fires—**M**	Medium	– Land management, fire protection	Medium	12.1.5.3, 12.5.4, 12.5.10
	– Weed invasion—**M**	Medium	– Landscape management	Medium	12.4.3
Aquatic ecosystems	– Salinization of some coastal freshwater wetlands—**M**	High	– Physical intervention	Low	12.4.7
	– River and inland wetland ecosystem changes—**M**	Medium	– Change water allocations	Low	12.4.5, 12.4.6
	– Eutrophication—**M**	Medium in inland Aus. waters	– Change water allocations, reduce nutrient inflows	Medium to low	12.3.4
Coastal ecosystems	– Coral bleaching, especially Great Barrier Reef—**H**	High	– Seed coral?	Low	12.4.7
	—More toxic algal blooms?—**VL**	Unknown	—	—	12.4.7
Agriculture, grazing, and forestry	– Reduced productivity, increased stress on rural communities if droughts increase, increased forest fire risk—**M**	Location-dependent, worsens with time	– Management and policy changes, fire prevention, seasonal forecasts	Medium	12.5.2, 12.5.3, 12.5.4
	– Changes in global markets as a result of climate changes elsewhere—**H**, but sign uncertain	High, but sign uncertain	– Marketing, planning, niche and fuel crops, carbon trading	Medium	12.5.9
	– Increased spread of pests and diseases—**H**	Medium	– Exclusion, spraying	Medium	12.5.7
	– Increased CO_2 initially increases productivity, but offset by climate changes later—**L**	Changes with time	– Change farm practices, change industry		12.5.3, 12.5.4
Horticulture	– Mixed impacts (+ and -), depends on species and location—**H**	Low overall	– Relocate	High	12.5.3

Table 12-2 (continued)

Sector	Impact	Vulnerability	Adaptation	Adaptability	Section
Fish	– Recruitment changes (some species)—**L**	Unknown net effect	– Monitoring, management	—	12.5.5
Settlements and industry	– Increased impacts of flood, storm, storm surge, sea-level rise—**M**	High in some places	– Zoning, disaster planning	Moderate	12.6.1, 12.6.4
Human health	– Expansion and spread of vector-borne diseases—**H**	High	– Quarantine, eradication, or control	Moderate to high	12.7.1, 12.7.4
	– Increased photochemical air pollution—**H**	Moderate (some cities)	– Emission controls	High	12.7.1

(to a lesser extent) New Zealand farmers have adapted, at least in part, to existing El Niño-related droughts, they depend on good years for recovery. Thus, despite their adaptability, they are quite vulnerable to any increase in the frequency of drought or to a tendency for droughts to last for a longer period. This vulnerability flows through to the rural communities that service them (see Section 12.5.6).

Several of these vulnerabilities are likely to interact synergistically with each other and with other environmental stresses. Moreover, vulnerability is a result of exposure to hazard and capacity to adapt. Thus, vulnerability will be greatly affected by future changes in demography, economic and institutional capacity, technology, and the existence of other stresses.

There have been no rigorous studies for Australia or New Zealand that have taken all of these variables into account. Thus, Table 12-2 is based largely on studies that assume that the society that is being impacted is much like that of today. It should not be assumed, however, that socioeconomic changes in the future necessarily will reduce vulnerability in Australia and New Zealand. Indeed, many existing socioeconomic trends may exacerbate the problems. For instance, the bias toward population and economic growth in coastal areas, especially in the tropics and subtropics, by itself will increase exposure to sea-level rise and more intense tropical cyclones. If such trends are not to increase vulnerability, they will need to be accompanied by a conscious process of planning to reduce vulnerability by other means (e.g., changes in zoning and engineering design criteria). Thus, vulnerability estimates are based on present knowledge and assumptions and can be changed by new developments, including planned adaptation.

12.9.7. Knowledge Gaps

Significant knowledge gaps have become apparent during this assessment. These gaps mean that the net cost or benefit of unmitigated climate change in Australia and New Zealand is highly uncertain (see Section 12.9.1) and cannot be compared objectively with the cost of mitigation. Without this knowledge base, policymaking regarding adaptation and mitigation cannot be soundly based on economic considerations. Research priorities follow.

Indicators of climate impacts: Although long-term monitoring programs are in place for physical indicators (such as climate variables and sea level), work is still desirable on designing and implementing long-term monitoring programs that cover vulnerable animals, plants, and ecosystems and systematically examining them for the effects of climate changes. Flora and fauna with presently restricted or marginal climatic ranges would be most appropriate (see Section 12.4). (Candidate indicators for the UK are presented in Cannell *et al*., 1999.)

Underpinning physical knowledge and improved scenarios: Improved impact assessments will depend on better understanding of how climate change may influence factors such as the frequency and intensity of El Niños and related droughts, the intensity and location-specific frequency of tropical cyclones, and return periods for heavy rainfalls, floods, high winds, and hail. Oceanic issues include understanding differences between observed and modeled lag in warming of the Southern Ocean (see Section 12.1.5.2), possible impacts of cessation of bottomwater formation (see Section 12.4.7), and determining the influence of greenhouse warming on currents, upwelling, and nutrient supply. More knowledge is needed about influences of GHG-related cooling in the stratosphere on ozone depletion and regional UVradiation levels (see Section 12.7.1). All of this knowledge is needed to improve scenarios of regional climate (including ocean behavior).

Underpinning biological knowledge: The sensitivities of many plant and animal species and ecosystems in this region to climate changes, as well as the potential threats to biodiversity, are still unknown (see Section 12.4). Knowledge is required for assessment of potential impacts and for development of conservation strategies. This is important for marine and coastal environments, including coastal freshwater wetlands (see Section 12.4.7), as well as for terrestrial systems. Identification of relevant climatic thresholds for biological (and other) systems is needed (see Section 12.8.2). The effects of the time-varying balance between the beneficial physiological effects of increasing CO_2 concentrations and climate change on natural (indigenous) and managed ecosystems needs to be better understood, especially in light of recent regional scenarios.

Underpinning social knowledge: Better knowledge is required about the vulnerability of particular population groups (including indigenous people), about how people and organizations have adapted to past climate variability and changes, and about public attitudes to adaptation and mitigation options. Work is needed to understand how different socioeconomic futures (demography, economic capacity, and technological change) (see Section 12.1.5.4) would affect vulnerability (see Sections 12.8 and 12.9.2.2) and on socioeconomic thresholds for change, such as economic nonviability and unacceptable risk.

Fisheries: There is insufficient information to enable confident predictions of changes in fisheries productivity from climate change (see Section 12.5.5). This requires better knowledge of physical and biological processes in the ocean (as above) and improved information on the climate sensitivities of many species.

Health: Continuing work is needed on the potential for introduction (New Zealand) and spread (Australia) of significant disease vectors, including sensitivity to climate, population shifts, and effectiveness of health services and biosecurity procedures (see Section 12.7.4). Other health issues should be addressed, including potential effects of threats to water supply on remote communities (see Section 12.7.6).

Regional effects and integration: Better quantitative sectoral knowledge is required about, for example, influences of climate change on water supply and demand (see Section 12.3.1), salinization (see Section 12.3.3), and some crops and farming practices (see Sections 12.5.2 and 12.5.3). Because various sectors (e.g., agriculture, ecosystems, infrastructure, and hydrology) interact at the regional and national levels, continued work is needed on integrated assessment approaches and models that synthesize sectoral knowledge and draw on the social sciences (see Section 12.8.2), in rural and urban settings. Models of the physical economy that track fluxes and pools of materials, energy, land, and water are required for national analyses.

Global interactions: More understanding is needed of the interaction of global climate change impacts, and of mitigation policies, on Australian and New Zealand markets, sectoral change, and land use (see Sections 12.5.9 and 12.8.7).

Adaptation: Further objective studies are required, in close collaboration with stakeholders, on adaptation options and their acceptability, costs, co-benefits, side effects, and limits (see Section 12.8). Adaptation should be regarded as a means to maximize gains and minimize losses, with a greater exploration of opportunities (see Section 12.8.1).

Costing: More comprehensive and realistic costings are needed for impacts and adaptation options, taking account of human behavior and using up-to-date scenarios.

Communication of policy-relevant results: If climate change issues are to be addressed by decisionmakers, there will need to be better communication of results from research. This will come partly from consultation with decisionmakers and other stakeholders to ensure that the right policy-relevant questions are addressed (see Sections 12.8.2 and 12.9) and partly from effective communication of what is known, as well as the uncertainties. A risk-assessment approach geared to particular stakeholders seems likely to be most effective (see Section 12.9.5).

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