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William Hare:

Assessment of Knowledge on Impacts of Climate Change – Contribution to the Specification of Art. 2 of the UNFCCC

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"Welt im Wandel: Über Kioto hinausdenken.
Klimaschutzstrategien für das 21. Jahrhundert"

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Autor: William Hare
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Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen
Geschäftsstelle
Reichpietschufer 60–62, 8. OG.
10785 Berlin

Telefon (030) 263948 0
Fax (030) 263948 50
E-Mail wbgu@wbgu.de
Internet http://www.wbgu.de

Assessment of Knowledge on Impacts of Climate Change – Contribution to the Specification of Article 2 of the UNFCCC: Impacts on Ecosystems, Food Production, Water and Socio-economic Systems

Mr. William Hare
Visiting Scientist
Potsdam Institute for Climate Impact Research
Potsdam, Germany

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List of Figures

List of Tables

1. Introduction

The purpose of this report is to compile and summarise the present knowledge on impacts of climate change as a basis for a consideration of what may constitute dangerous anthropogenic interference with the climate system under Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC). An attempt will be made to associate projected global mean surface temperature and/or sea level changes with specific identified impacts and effects in order to assist a discussion on the operationalization of Article 2. The main emphasis will be on ecosystem effects, food production, water resources, and sustainable development. Whilst the starting point for this work will be the findings of the Intergovernmental Panel on Climate Change Third Assessment Report (IPCC TAR), it will be heavily supplemented by the underlying scientific literature used in the TAR as well as more recent studies published since the conclusion of the TAR in September 2001.

The organization of the report is as follows. In this section the context for the current assessment is outlined including background information on Article 2 of the UNFCCC, the WBGU tolerable window and the broad findings of the IPCC TAR. Section 2, on ecosystems, biodiversity and climate change, will review a range of projected impacts on ecosystems and species. Section 3 summarizes projected effects on food security, water supply and economic activities. Section 4 will briefly summarize the information presented in this report.

UNFCCC Article 2 – preventing dangerous anthropogenic interference

The ultimate objective of the United Nations Framework Convention on Climate Change, as specified in its Article 2, is the stabilization of greenhouse gas concentrations at levels that "would prevent dangerous anthropogenic interference with the climate system". Such levels should be achieved "within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner" (UN 1992). It can be seen that Article 2 has several interrelated elements, which may be linked to other parts of the Convention. Article 3.3 is of particular relevance here, relating, as it does, to the application of the precautionary principle in the face of scientific uncertainty.

Under Article 2, stabilization of greenhouse gas concentrations at some arbitrary level is not the objective *per se*, as is sometimes assumed, but rather at a level that would "prevent dangerous anthropogenic interference with the climate system". There is no specific reference to the manner in which this stabilization should be achieved. It is open, for example, as to whether greenhouse gas concentrations would rise above the ultimate stabilization level before falling back, provided that in the end interference with the climate system is prevented. The second part of Article 2, in effect, establishes a set of criteria and general requirements for the timeframe in which greenhouse gas concentrations must be stabilized. In other words, one could identify levels of impacts on the areas mentioned that resulted in, for example, threats to food production and work backwards to compute concentrations of greenhouse gases and/or the time profile of these concentrations that would prevent these impacts from occurring.

Article 2 requires that greenhouse gases be stabilized in such a way and within a timeframe that ecosystems can adapt naturally, food production is not threatened and that economic development is able to proceed in a sustainable manner. Put another way, if stabilization were achieved in such a way that all of these requirements were met, then it could be said that dangerous anthropogenic interference with the climate system had been prevented, provided that no other interference with the climate system was being caused that could be classified as dangerous. If one or the other element were not met, then there would be a breach of the Convention's objective.

It may be useful to note at the outset that Article 2 talks of prevention of "dangerous anthropogenic interference with the climate system" and is not necessarily limited to dangerous climate changes *per se*. In theory at least, dangerous anthropogenic interference could relate to a variety of human induced changes in the totality of the climate system, which people and/or governments could consider dangerous. Examples of such issues could include, for example, the risk of ice sheet instability or irreversible decay. If, for example, the West Antarctic Ice sheet turned out to be very sensitive to global warming, it is conceivable that its collapse could be triggered by levels of greenhouse gases that did not result in immediate threats (within the next decades to century) to any of the categories of effects cited in Article 2. Nevertheless, such a risk, with the entailed 6-7 metres of sea level rise over centuries to millennia, would be considered by many as dangerous (O'Neill and Oppenheimer 2002).

What may constitute dangerous anthropogenic interference with the climate system?

To date, the UNFCCC itself has not attempted to define what may constitute dangerous anthropogenic interference with the climate system or what acceptable limits may be to impacts on ecosystems, food production or economic development.

Nevertheless, over the past decade or so several groups have sought to identify acceptable limits to climate change. There have been two broad approaches, often combined. One is based on a "bottom up" assessment of the projected impacts of climate change on ecosystems, agriculture and other sectors. The other is based on a "top down" approach which focuses on avoiding greater changes than are thought to have occurred in the current and the last few interglacial periods. The objective of this approach is, in effect, to keep the climate system away from situations (greenhouse gas concentrations) where the projected temperatures are either not known from earlier warm periods or are associated with past periods of rapid and abrupt change.

Based on a review of estimated impacts on ecosystems, as well as comparison of projected climate changes with "normal climatic changes" of the past (e.g. over the

Holocene and not periods of abrupt damages associated with glacial termination), the WMO/ICSU/UNEP Advisory Group on Greenhouse Gases (AGGG), in 1990, identified two main temperature indicators or thresholds with different levels of risk (Rijsberman and Swart 1990). It was argued that an increase of greater than 1.0°C above pre-industrial levels "may elicit rapid, unpredictable and non-linear responses that could lead to extensive ecosystem damage" with warming rates above 0.1°C/decade likely to lead to rapidly increasing risk of significant ecosystem damage. Furthermore, a 2.0°C increase was determined to be "an upper limit beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly".

Corresponding indicators for sea level rise were also developed. It was argued that rates of sea-level rise of less than 20mm/decade "would permit the vast majority of vulnerable ecosystems, such as natural wetlands and coral reefs to adapt with rates beyond this leading to rapidly rising ecosystem damage" (Rijsberman and Swart 1990: viii). The AGGG felt that limiting total sea level rise to a 50 cm increase above 1990 global mean sea-level could "prevent the complete destruction of island nations, but would entail large increases in the societal and ecological damage caused by storms". This assessment was based on the scientific knowledge available before the IPCC First Assessment Report was concluded in 1990.

In 1995, the WBGU used a "top down" approach to determine an upper limit or "tolerable window" of warming. Adding 0.5°C to the estimated difference between the recent, pre-industrial Holocene and the warmest period of the last interglacial, the WBGU arrived at a tolerable warming window (relative to pre-industrial temperatures) of 2°C (WBGU 1995). This limited additional future warming to around 1.3°C, relative to the estimated 1995 global mean temperatures. Above this limit, it was argued, was a risk of "dramatic changes in the composition and function of today's ecosystems" (WBGU 1995: 7).

At a political level, the European Union's Environment Council agreed in 1996 that global temperatures should not be allowed to exceed 2°C above pre-industrial levels (European Community 1996):

> *"Given the serious risk of such an increase and particularly the very high rate of change the Council believes that global average temperatures should not exceed 2 degrees (Celsius) above pre-industrial level and that therefore concentration levels lower than 550 (parts per million of) CO_2 should guide global limitation and reduction efforts. This means that the concentrations of all greenhouse gases should also be stabilised. This is likely to require a reduction of emissions of greenhouse gases other than CO_2, in particular CH_4 and N_20."*

The Environment Council based this decision on a consideration of the IPCC Second Assessment Report and the impacts identified therein, which in general were for a doubling of CO2 above pre-industrial levels.

The IPCC itself has not directly addressed the question of what might be dangerous climate change and has seen its role as limited to providing policy relevant but not policy prescriptive advice. In the lead up to the Second Assessment Report, the IPCC held a workshop in Fortaleza, Brazil in 1994 on the issue of Article 2, however the results of this were inconclusive, except for the reaffirmation by scientists that they did not see a role for themselves as a group in defining the limits of Article 2.

In its Third Assessment Report the IPCC made several efforts to provide scientific advice that could be used by policy makers in relation to Article 2. Chapter 19 of the Working Group II report, which attempted to synthesize the other chapters in this working group report, identified five "reasons for concern" that could be used to "aid readers in making their own determination about what is 'dangerous' climate change" (Smith *et al.* 2001: 915):

1) The relationship between global mean temperature increase and damage to or irreparable loss of unique and threatened systems;
2) The relationship between global mean temperature increase and the distribution of impacts;
3) The relationship between global mean temperature increase and global aggregate damages;
4) The relationship between global mean temperature increase and the probability of extreme weather events;
5) The relationship between global mean temperature increase and the probability of large-scale singular events such as the breakup of the West Antarctic Ice Sheet or the collapse of the North Atlantic thermohaline circulation.

The present report will provide information relevant to factors one to three, with the latter two reasons for concern being beyond the scope of this report.

The Synthesis Report of the IPCC TAR sought to answer nine policy relevant questions developed in consultation with the UNFCCC, several aspects of which were relevant to Article 2. The most pertinent to the present work are from questions three and six in the synthesis report:

> Question 3: "What is known about the regional and global climatic, environmental, and socio-economic consequences in the next 25, 50, and 100 years associated with a range of greenhouse gas emissions arising from scenarios used in the TAR (projections which involve no climate policy intervention)? To the extent possible evaluate the ...Projected changes in atmospheric concentrations, climate, and sea level … impacts and economic costs and benefits of changes in climate and atmospheric composition on human health, diversity and productivity of ecological systems, and socio-economic sectors (particularly agriculture and water) ..." (IPCC 2001: 8).

> Question 6: "How does the extent and timing of the introduction of a range of emissions reduction actions determine and affect the rate, magnitude, and impacts of climate change, and affect the global and regional economy, taking into account the historical and current emissions? What is known from sensitivity studies about regional and global climatic, environmental and socio-economic consequences of stabilizing the atmospheric concentrations of greenhouse gases (in

> carbon dioxide equivalents), at a range of levels from today's to double that level or more, taking into account to the extent possible the effects of aerosols?" (IPCC 2001: 19).

Though there were attempts, in various drafts of the IPCC TAR, to associate specific global mean temperature increases with defined impacts, by the time the report was finalized most of these examples were reduced to quite general statements in the summaries for policy makers of Working Group II and the Synthesis Report. However, the full Synthesis Report does contain several tables outlining identified impacts for temperature bands in each of the areas relevant to this paper. Whilst there are limitations to these tables, notably that the temperature bands associated with specific impacts are often too large and hence lose some precision, such as is possible given all other uncertainties, they will be used as the starting point for the analysis in each of the sections of this report. Indeed, this may provide the best and most coherent way of showing transparently how the analysis presented in this paper builds upon, extends or diverges from the conclusions of the TAR authors.

2. Ecosystems, Biodiversity and Climate Change

Ecosystems and their species form the fabric of life on the Earth and provide a very wide range of services to humanity. The IPCC TAR has summarized these and in any event they are well known (Table 1). Unfortunately, given the large human pressures and impacts on species and ecosystems, rapid climate change probably could not happen at a worse time in the history of the biosphere (Soulé 1992). Due to these pressures species are becoming extinct at a rate 100-1000 times greater than is considered normal over evolutionary time. As a consequence conservation biologists have labelled the current epoch the sixth major extinction event in the history of the planet (Chapin *et al.* 2000; Novacek and Cleland 2001). The causes of this are anthropogenic in origin, principally the modification or destruction of habitats, pollution, hunting, resource use, and the introduction of exotic species. Large fractions of extant species groups are classified as endangered (see Figure 1).

Species extinction results in loss of biodiversity and often changes in the structure and function of ecosystems. There is a large risk that many of the ecosystem services identified in Table 1 could be adversely effected by species loss. However, the ability to predict which species are the most important is very often quite limited (National Research Council 1999; Chapin *et al.* 2000).

Table 1 - Ecosystems Function with Links to Good/Services and Possible Societal Value

Function	Goods/Service	Value
Production	– Food – Fiber (timber and non-wood products) – Fuel – Fodder	Direct
Biogeochemical cycling	– Nutrient cycling (especially N and P absorption/deposition) – Carbon sinks	Mostly indirect, although future values have to be considered
Soil and water conservation	– Flood and storm control – Erosion control – Clean water – Clean air – Water for irrigation – Organic matter or sediment export – Pollution control – Biodiversity	Mostly indirect, although future values have to be considered
Animal-plant interactions	– Pollination – Animal migration – Biodiversity	Mostly indirect, future, bequest, and existence values have to be considered
Carrier	– Landscape connectivity – Animal migration – Biodiversity – Aesthetic/spiritual/cultural service	Mostly indirect and existence, but bequest may have to be considered

Source: Compiled from information in Figure 5-1 of Gitay *et al.* (2001).

Although it is clear that climate change is only one of several pressures on ecosystems, and often not the most immediate (Sala *et al.* 2000), one must also consider that the interaction between human activities and their effects on ecosystems and species is likely to exacerbate the effects of climate change. For a number of ecosystems and species it seems clear that if non-climatic pressures are successfully relieved but climatic ones grow, there is still a substantial likelihood of major losses or extinctions in the coming century (and in some cases several decades).

Significant and systematic effects have been observed on a very wide range of species and ecosystems globally which have been attributed to climate change (McCarty 2001; Walther *et al.* 2002; Parmesan and Yohe 2003; Root *et al.* 2003). Space does not permit elaboration of these findings here: it is sufficient to note that a large majority of observational studies reveal changes consistent with expected effects of climate change.

The rest of this section examines the basic processes leading to climatic impacts on species and ecosystems followed by a review of the projected effects of climate change on a range of species and ecosystems. The starting point for this review is the IPCC Third Assessment Report findings, particularly those of Working Group II, however the main effort is to attempt to estimate the effects of climate warming on a sample of species and ecosystems drawn from the literature. Thus a substantial volume of publications and reports not reviewed in the TAR, but which are relevant to an assessment of climate effects on ecosystems, were sought out and reviewed. Much literature has been published since the TAR or was not available to the authors at the time of its writing (a large selection of this is listed in the Appendix to the IPCC Technical Paper on Climate Change and Biodiversity (Gitay *et al.* 2002)). This sample will be representative of the wide range of impact studies in the literature at present, but is by no means comprehensive.

The IPCC Third Assessment Report reviewed the impacts of climate change on wildlife and ecosystems in various chapters of the Working Group II Report. Chapter 5 of that report (Gitay *et al.* 2001) is the main locus of this review. It covered the effects of global climate change on the terrestrial biosphere, wildlife in ecosystems, grasslands, savannas, and deserts, forests and woodlands, lakes and streams, inland wetlands, and arctic and alpine ecosystems.[1] In addition to the material found in Chapter 5, Price *et al.* (2000)[2] prepared supplementary information. The impacts of climate change on coastal zones and marine ecosystems were reviewed in a separate chapter and much additional material on Arctic and Antarctic ecosystems were reviewed in the polar chapter. In addition, the regional chapters of this report (Africa, Asia, Small Island States, North America, Latin America, Australia and New Zealand, and Europe) provide a lot of additional material on ecosystems and species effects not covered in Chapter 5. Finally, Chapter 19 attempted a synthesis of the findings of the complete Working Group II Report (Smith *et al.* 2001).

A huge volume of literature is reflected in the TAR assessment and it is neither desirable nor feasible to reconstruct this, hence, the effort here has focused on identifying key findings and studies which can provide the basis for an assessment of the projected impacts of climate change on species and ecosystems by degrees of projected warming or sea level rise. Nevertheless, substantial effort has been made here to at least verify the reviews cited in relevant chapters of the TAR that relate to this objective.

Processes causing loss of biodiversity and ecosystem damage

Climate change is expected to affect ecosystems and species in a variety of different ways. In this section the general processes, by which increased CO_2 and climate change affect species and ecosystems, are outlined. Specific examples are discussed in the later sections that deal with specific classes of species and ecosystem types.

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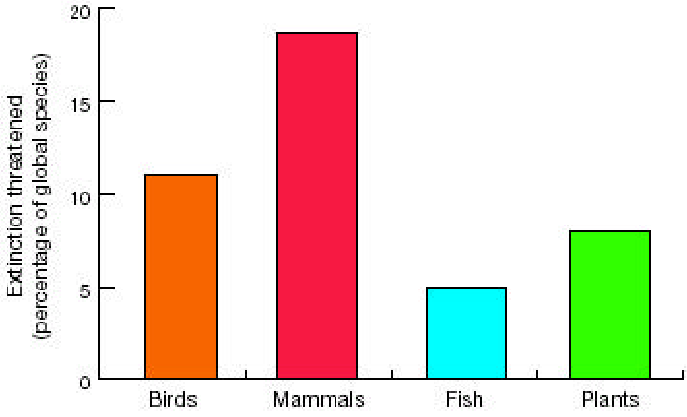
[1] See http://www.grida.no/climate/ipcc_tar/wg2/196.htm.

[2] See http://www.usgcrp.gov/ipcc/html/ecosystem.pdf.

Figure 1 - Proportion of the Global Number of Birds, Mammals, Fish and Plants Species that are Currently Threatened with Extinction



Source: Figure 2 from Chapin *et al*. (2000).

The species that are most vulnerable to extinction from whatever cause are those with restricted ranges, fragmented distribution within their range, low populations, reducing range, decreasing habitat within the range, and/or which are suffering population declines (Price *et al.* 2000). Species with quite restrictive habitat requirements are most vulnerable to extinction (Pimm *et al.* 1995). Where climate change is projected to reduce habitats of such species there is likely to be the greatest extinction risks. Examples from the IPCC TAR include the Bengal tiger and its habitat in the Sundarbans and several mountain dwelling species from Africa and Central and South America. In the case of the Sundarbans, this World Heritage listed mangrove and forested wetland habitat is projected to be reduced substantially as a consequence of sea level rise. Potential migration routes for many of the area-dependent species are blocked by human activities (ADB 1994).

Table 2 summarizes an array of factors known to drive the processes of species endangerment and extinction. Climate change is one of the pressures that is or is likely to act to increase species vulnerability now and in the future. However, it will often, if not usually, act in combination with the other pressures described below. Habitat fragmentation caused by destruction of habitat, infrastructure or disturbance is likely to exacerbate the effects of climate change by reducing the migration and dispersal ability of species (Malcolm *et al.* 2002b). Pollution may also reduce the ability of species to cope with the stresses of rapid climate change (Hojer *et al.* 2001).

Table 2 - Processes driving Species Endangerment and Extinction

Process	Explanation
Conversion of natural lands to other uses	This is the main threat to ecosystems and wildlife. 80% of the earth's forests are already cleared or degraded and a sizeable fraction of the remainder is threatened.
Habitat fragmentation	This can be caused by agricultural land use and infrastructure such as roads, railways and urban areas. Habitat fragmentation threatens the long term viability of wildlife population as: • Species often require large areas to survive in the long term. At present, a number of large birds and mammals have range requirements greater than the remaining habitat area. This means that in the longer term they are likely to decline due to the effects of accidents, inbreeding or climate change. • Fragmentation is in effect a barrier to the dispersal and migration of species in response to natural disturbances or climatic changes. • Invasion by exotic species such as new predators is easier.
Habitat degradation	Human use of habitats for natural resource extraction or recreation can introduce exotic predators (e.g. cats, dogs), plant pathogens, disturb water courses or water quality or disturb breeding environments by noise or physical disturbance.
Hunting and extraction or use of natural resources	Hunting, harvesting, culling or inadvertent killing of wildlife is a substantial threat in many, if not most, regions. Threats arise in a variety of ways: • Hunting and harvesting is often not sustainable and has, in the past, led to extinctions or stock collapses. Well known historical examples include the extinction of the great Auk and the passenger pigeon. In recent years, hunting in Europe has led to a decline in the European Robins populations. In developing countries wildlife populations adjacent to expanding urban areas will most likely not be sustained. • By-catch losses are often significant. • Culling of wildlife because of actual or perceived competition with human activities. • Hunting can result in pollution of wetlands.
Wildlife trade	This can place considerable pressure on populations and species and has caused substantial damage to large mammals such as elephants, rhinoceros, and tigers.
Pollution	Pollutants have been detected in many species throughout the world. Pollution has been implicated in the decline of a number of species through: • Direct poisoning. • Indirect effects, due to longer-term exposure to pollutants, on reproduction, behaviour and survival. • The elimination or modification of habitat.
Exotic species	Introduced species have caused substantial damage to local species and pose a threat to substantial numbers of mammals and birds.

Process	Explanation
Climatic change	Climate is an important determining factor of the distribution range of ecosystems and species. Future projected rates of change appear to exceed previously observed ones, giving rise to concerns as to the ability of species and ecosystems to adapt to projected changes without significant loss or disruption.
Synergistic effects of climate change	Climate change is likely to act synergistically with many of the other factors mentioned in this table. Habitat fragmentation and loss will inhibit species abilities to migrate in response to climate changes. Exotic species invasion may be facilitated by a combination of habitat degradation and climate change, yielding negative effects on the endemic species. Human responses to climate change may exacerbate threats to biodiversity, by, for example, preventing inland movement of coastal wetlands or as a consequence of increased pesticide use resulting from enhance pest activity in changed climatic conditions.
Extreme climatic events	Extreme climatic events and changes in the pattern of weather and climate events can cause large-scale losses of species and damages to ecosystems.

Source: This table has been compiled based on the review of Gitay *et al*. (2001) and (Hughes 2000).

One of the important processes to bear in mind, when considering biodiversity loss and ecosystem decay, is the observation that species, or populations of species, that have survived large scale loss of their habitat in the past may still face extinction (Cowlishaw 1999). Species often require large areas of habitat to be able to weather stochastic events such as droughts and disease outbreaks, avoid the problems of small gene pools or other environmental pressures and thus survive in the long-term.

Climate change and CO_2 effects on species and ecosystems

Projected anthropogenic climatic change and increases in CO_2 are expected to result in large changes in ecosystems globally and to add significantly to the pressure on species from the human activities outlined in Table 2. In a general sense, species respond to warming by moving their ranges upwards and polewards. Within this general pattern however, the range and complexity of responses expected is quite large. Nevertheless, these can be broken down into a finite list of classes of responses or impacts, which are summarized in Table 3. Examples of some of the potential impacts and risks are also given. Hughes (2000) provides a very useful schematic of the main pathways by which climate change and increases in CO_2 can result in negative impacts on species and ecosystems (see Figure 2). Increasing CO_2 concentrations impact on plant species directly affecting growth, nutrient uptake, and water use efficiency.

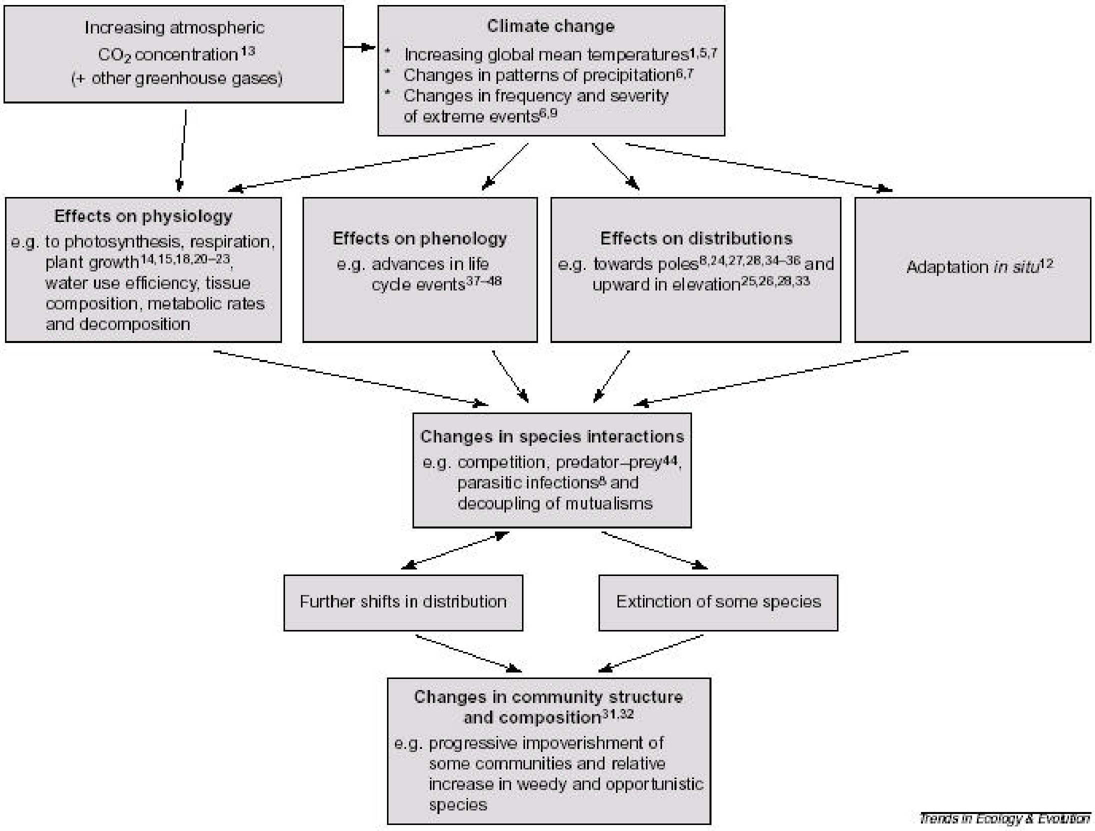


Figure 2 - Pathways by which Climate change affects Species and Ecosystems

Source: Figure 2 of Hughes (2000). Reference numbers in this figure refer to the original publication by Hughes.

CO_2 (and other greenhouse gases) induced climate changes will result in changes in temperature, the precipitation regime and the frequency and intensity of extreme events. Species response can be divided into four groups – changes in physiology, phenology, distribution and *in situ* adaptations. The various responses ultimately lead to changes in species interaction and consequently, to changes in ecosystem structure and composition.

Changes in the frequency and intensity of extreme events as a consequence of climate change, including El Niño cycles, are likely (Easterling *et al.* 2000) and will have large effects upon species and ecosystems (Parmesan *et al.* 2000). Average climate changes may not be as important as the changes in extremes of weather and climate in triggering shifts in species and/or major changes in ecosystems. To date, few studies have taken this into account in projecting the effects of climate change on species.

Beyond the details of what mechanisms and processes will drive species and ecosystem responses to climate change, is the apparent fact that the rate of global mean surface temperature change projected over the next century appears quite unprecedented, at least during the Holocene and perhaps for much longer. The maximum rate of global mean change consistent with the range of estimates for the transition from the last glacial maximum to the Holocene (also known as Termination I) is around 0.01°C/decade[3]. A 3-5°C warming to 2100 is thus about 25-45 times faster than the highest rates of change at the end of the last glacial over several thousand years.

In relation to century scale changes, it would appear that changes with rates of more than 0.1°C/decade are quite unusual. If one compares the maximum trends in temperature over varying time periods in ice core data and in proxy and instrumental records, it is apparent that the maximum rates of change drop rapidly with increasing averaging period. Figure 3 compares a local long-term temperature series with three hemispheric or global average records for the period 1861-2001. As would be expected the local temperature series shows much larger variability. In Figure 4 rates of change in temperature are calculated from the individual time series, over all possible trend periods in each record and then the maximum rate for each trend period found. For example, the maximum trend in temperature over all 30-year periods in the Mann *et al.* (1999) 1000-year record is 0.2°C/decade, whereas for the central England record it is close to 0.5°C/decade. For a 100-year trend period, the maximum rate of change observed is less than 0.1°C per decade for all records, excepting projected changes over the next century.

The projected rates of change, in relation to the ability of plants and animals are to move, migrate or adapt over the next century worry many scientists (Overpeck *et al.* 1992; Malcolm *et al.* 2002b). During the last deglaciation, even widespread and dominant species became extinct (Jackson and Weng 1999) and there is concern that projected rates of climate change exceed the observed rates of change in the past (Davis and Shaw 2001; Malcolm *et al.* 2002b). Whilst attempts have been made to model migration and movement of plants under climate change, present methodologies remain problematic (see discussion in Gitay *et al.* (2001)). Although there is a general consensus that projected rates of climate change are very likely to exceed the migrational capacity of species in at least the mid- and high-latitudes, too little is known to be able to fully quantify this problem.

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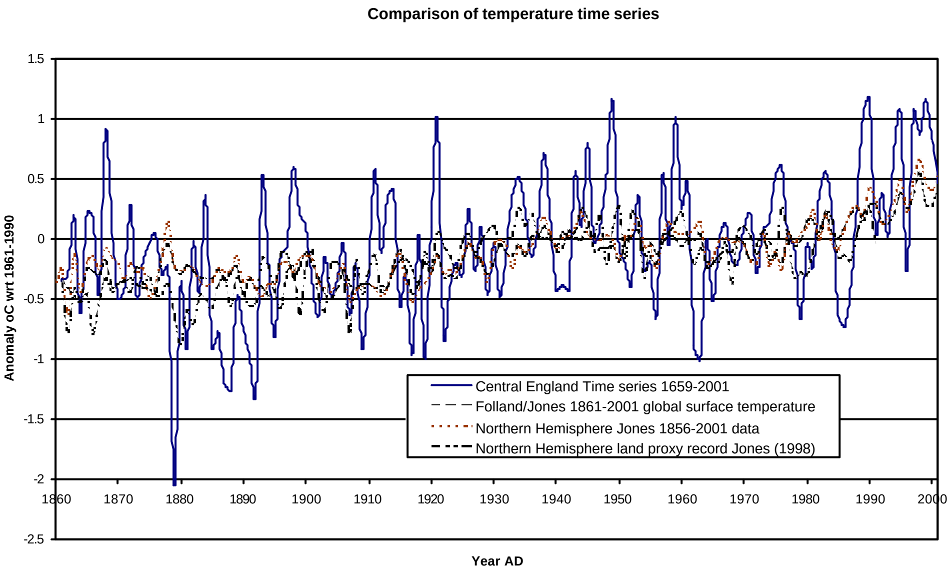
[3] In the somewhat extreme case that Termination I was associated with an 8°C change in global average temperature over a period of 7,000 years as may be inferred from the Vostok record published by (Petit *et al.* 1999).

Table 3 - Response and Impacts of Climate Change on Species and Ecosystems

Response or impact	Examples of effects and risks
• Changes in distribution of species, ecosystem boundaries, and biomes	Poleward or upward shift of aquatic and terrestrial biota (McCarty 2001; Walther *et al.* 2002; Root *et al.* 2003). Risk that insufficient altitudinal range with suitable habitat exists for mountain species to migrate (Theurillat and Guisan 2001). Risk that rate of change exceeds migratory capacity of species (Malcolm *et al.* 2002b).
• Changes in phenology of biotic and abiotic processes and events	Earlier flowering of plants and budding of trees, earlier egg laying in birds. Risk of asynchronous timing of events between species with tight synchronization requirements e.g. late arrival of migratory birds after peak of food availability has passed (Both and Visser 2001; Visser and Holleman 2001).
• Changes in structure of plant communities	Changes from grassland or savannah to woodlands, or from moist tropical forest to drier woodlands. Risk of loss of habitat for ungulates with reduction in savannah and invasion with woody plant species (Bond and Midgley 2000).
• Changes in species composition and diversity	Loss of climatically suitable habitat for species may frequently lead to range reductions, population fragmentation and reduced genetic diversity. Risk of major species loss in some regions and risk of ecosystem structural changes or loss if key species disappear (Kerr and Packer 1998; Midgley e al. 2002).
• Changes in animal and plant population dynamics and structure	Changes in competitive balance between species affecting ecosystem structure and composition.
• Changes in Net Primary Productivity (NPP), Net Ecosystem Productivity (NEP), Net Biome Productivity (NBP)	Increased CO2 and warmer temperatures will lead to changes, often increases, in NPP, with the balance of ecosystem productivity NEP and NBP being determined by the precipitation changes (Cramer et al. 2001). Risk in some ecosystems of reduction in NPP, NEP or NBP with warming in the coming century (White et al. 2000a; Friedlingstein et al. 2001).
• Changes in carbon and nutrient cycling	Changes in NPP, NEP and NBP affect global carbon cycle with increasing CO_2 likely to enhance the terrestrial uptake of carbon (Lucht *et al.* 2002). Risk of positive feedback from climate change to terrestrial carbon cycle (White *et al.* 2000a; Friedlingstein *et al.* 2001).
• Changes in litter, forage and wood quality	Increase atmospheric CO_2, whilst enhancing plant growth may at the same time results in less nutrient content in leaves (Tuchman *et al.* 2002), forage (Lenart *et al.* 2002) and crops (Reyenga *et al.* 1999). Kanowski (2001) finds that increased CO_2 will reduce the food quality of rainforest trees for tree dwelling marsupials, which is likely to reduce their abundance in the future.
• Changes in water-use efficiency with elevated CO_2	Could increase the drought resistance of plant species and with differential response between species, change the competitive balance between components of ecosystems (Bond and Midgley 2000).
• Increase in frequency and/or intensity of disturbance (e.g., fires)	Increased fire frequency in Mediterranean ecosystems as a consequence of changed drought intensity or frequency leading to shifts in vegetation structure (Parmesan *et al.* 2000; White *et al.* 2000b; Mouillot *et al.* 2002; Walther *et al.* 2002).
• Changes in water flow and level leading to loss of aquatic habitats, waterfowl, riparian forests, recreational opportunities, eutrophication	Changes in water regime (flow, duration and extent) can negatively affect the habitats and breeding possibilities of many species. Risk of loss of cold freshwater fish species and of major reductions in breeding habitats for ducks and other waterfowl (Sorenson *et al.* 1998).
• Increased pests and diseases	Changes in climate in the boreal forests could lead to a greater frequency of pest outbreaks affecting boreal tree species (Ayres and Lombardero 2000; Volney and Fleming 2000).

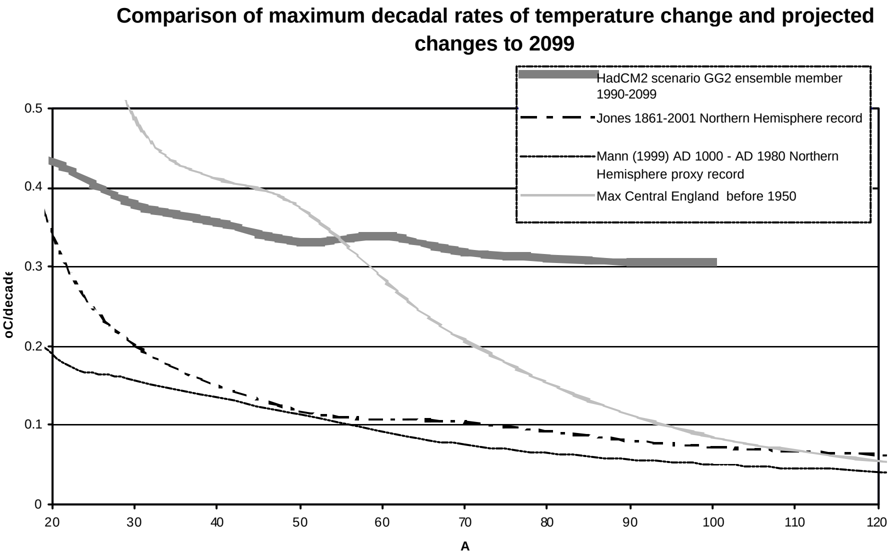
Note: This table is compiled in part from Figure 5-1 from Gitay *et al.* (2001), with the examples drawn from the literature.

Figure 3 - Comparison of Hemispheric and Long-Term Local Temperature Series



This graph compares the central England temperature series with a global mean and northern hemisphere surface instrumental record and a 1000 year proxy record for the northern hemisphere land surface for the period 1861-2000.

Figure 4 - Comparison of Maximum Decadal Rates of Change



This graph compares the maximum rates of change observed for different trend periods for three temperature records with a HadCM2 GCM projection for the period 1990-2099.

Projected effects on species and ecosystems

Table 4 from the IPCC TAR Synthesis Report is an attempt to summarize the findings of the IPCC TAR in relation to the impacts of climate change on ecosystems and species. It also attempts to place temperature-warming bands on the identified impacts for coral reefs, coastal wetlands and terrestrial ecosystems. What becomes apparent from examination of this table is that the risk of significant damages exists at low levels of warming. A detailed examination of the literature used in the TAR and that has been published subsequently adds substantial specificity to this picture.

Rather than present the analysis of the literature on the projected effects of climate change on ecosystems and species in a narrative format the results are presented in a table format. This facilitates cross comparison with similar systems in different regions as well as maintaining the compactness of this report. Table 5 details the results of the analysis here for a large number of projected impacts on species and ecosystems under quite different climate scenarios. An attempt has been made to reduce all of the scenarios used in the various studies cited to an estimated change in global mean surface temperatures that would correspond to the contemporary generation of climate models. This has been done using the simple climate model MAGICC 4.1 and the downscaling programme, SCENGEN of Wigley, Raper, Hulme and others (Hulme *et al.* 1995; Raper *et al.* 2001; Wigley and Raper 2001)[4]. Details are given in the table for each case.

Based on the analysis documented in Table 5 an attempt has been made to map the projected level of impact for different levels of warming graphically in (Figure 5-7). These figures attempt to associate some level of risk, loss or impact with a range of temperature increases. Five categories of risk were used in constructing the figures. Less

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[4] The programmes and references are available at http://www.cgd.ucar.edu/cas/wigley/magicc/installation.html

Table 4 - Ecosystem effects of climate change

	2025	2050	2100
CO_2 concentration[a]	405–460 ppm	445–640 ppm	540–970 ppm
Global mean temperature change from the year 1990[b]	0.4–1.1°C	0.8–2.6°C	1.4–5.8°C
Global mean temperature change from the years 1861-1890 (average)[5]	1.0-1.7°C	1.4-3.2°C	2.0-6.4°C
Global mean sea-level rise from the year 1990[b]	3–14 cm	5–32 cm	9–88 cm
Ecosystem Effects[c]			
Corals [WGII TAR Sections 6.4.5, 12.4.7, & 17.2.4]	Increase in frequency of coral bleaching and death of corals (high confidence[d]).	More extensive coral bleaching and death (high confidence[d]).	More extensive coral bleaching and death (high confidence[d]). Reduced species biodiversity and fish yields from reefs (medium confidence[d]).
Coastal wetlands and shorelines [WGII TAR Sections 6.4.2 & 6.4.4]	Loss of some coastal wetlands to sea-level rise (medium confidence[d]). Increased erosion of shorelines (medium confidence[d]).	More extensive loss of coastal wetlands (medium confidence[d]). Further erosion of shorelines (medium confidence[d]).	Further loss of coastal wetlands (medium confidence[d]). Further erosion of shorelines (medium confidence[d]).
Terrestrial ecosystems [WGII TAR Sections 5.2.1, 5.4.1, 5.4.3, 5.6.2, 16.1.3, & 19.2]	Lengthening of growing season in mid- and high latitudes; shifts in ranges of plant and animal species (high confidence[d]).[e,f] Increase in net primary productivity of many mid- and high-latitude forests (medium confidence[d]). Increase in frequency of ecosystem disturbance by fire and insect pests (high confidence[d]).	Extinction of some endangered species; many others pushed closer to extinction (high confidence[d]). Increase in net primary productivity may or may not continue. Increase in frequency of ecosystem disturbance by fire and insect pests (high confidence[d]).	Loss of unique habitats and their endemic species (e.g., vegetation of Cape region of South Africa and some cloud forests) (medium confidence[d]). Increase in frequency of ecosystem disturbance by fire and insect pests (high confidence[d]).
Ice environments [WGI TAR Sections 2.2.5 & 11.5; WGII TAR Sections 4.3.11, 11.2.1, 16.1.3, 16.2.1, 16.2.4, & 16.2.7]	Retreat of glaciers, decreased sea-ice extent, thawing of some permafrost, longer ice-free seasons on rivers and lakes (high confidence[d]).[f]	Extensive Arctic sea-ice reduction, benefiting shipping but harming wildlife (e.g., seals, polar bears, walrus) (medium confidence[d]). Ground subsidence leading to infrastructure damage (high confidence[d]).	Substantial loss of ice volume from glaciers, particularly tropical glaciers (high confidence[d]).

No climate policy interventions. Source: IPCC TAR Synthesis Report Technical Summary Table 3-2. *Refer to footnotes a-d accompanying Table 7 in this report. Note f: These effects have already been observed and are expected to continue [TAR WGII Sections 5.2.1, 5.4.3, 16.1.3, & 19.2].

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[5] Using Folland *et al.*(2001) global temperature data set.

Impacts on coastal wetlands

- Below a 1°C increase the risk of damage is low for most, but not all systems.
- Between 1-2°C moderate to large losses appear likely for a few systems. Of most concern are threats to the Kakadu wetlands and the Sundarbans of Bangladesh, both of which may suffer 50% losses at less than 2°C:
    - Inscribed on the UNESCO World Heritage List for both its outstanding natural and cultural values, Kakadu is regarded as one of the great wetlands of the world;
    - Also on the World Heritage list and renowned as the largest intact mangrove wetland system in the world, the Sundarbans is the sole remaining home of the Royal Bengal tiger (*Panthera tigris tigris*). Spanning about 1 million km^2, 62% of which is in Bangladesh and the remainder in West Bengal, India, this region is home to a wide variety and great number of species.
- Between 2-3°C, it is possible that the Mediterranean, Baltic and several migratory bird habitats in the US experience a 50% loss. In this range it seems likely that there could be the complete loss of Kakadu and the Sundarbans.

A key issue is the inertia of sea level rise, which makes the assignment of risk to different temperature levels misleading. Should, for example, sea level rise by 30cm in the coming decades to a century (threatening Kakadu), the thermal inertia of the ocean is such that an ultimate sea level rise of 2-4 times this amount may be inevitable even if temperature stops rising. The prognoses for wetlands in this context is not clear, as many damages are linked to the rate of sea level rise compared to the accretion and/or migratory capacity of the system. A major determinant of the latter will be human activity adjacent to, or in the inland catchments of the wetland system.

Impacts on animal species

Figure 6 summarizes estimated effects on a range of animal species. Along with the information in Table 5 one could conclude the following:

- Below 1°C warming, there appears to be a risk of extinction for some vulnerable species in southwestern Australia and to a lesser extent in South Africa. Range losses for species such as the Golden Bower bird in the highland tropical forests of North Queensland Australia and for many animal species in South Africa are likely to become significant and observable.

- Between 1-2^{o}C warming, large and sometimes severe impacts appear possible for some Salmonid fish habitats in the USA, the Collared Lemming in Canada, South African animals and for Mexico's fauna. Extinctions in southwestern Australia seem very likely and possibly South Africa and Mexico for the most vulnerable species. In general, many endangered species are pushed closer to extinction. Mid summer ice reduction in the Arctic ocean seems likely to be at a level that would cause major problems for polar bears at least at a regional level.

- Between 2-3oC large to severe impacts appear likely for Mexican fauna, many South African animals, the Collared Lemming in the Arctic (which would have broad implications for arctic ecosystems), Salmonid fish in Wyoming, with the likelihood of extinctions in Mexico and South Africa. In Hawaii, extinction of several Hawaiian Honeycreeper has been predicted for about a 2.8-3.2oC increase. In this range the Golden Bower bird's range would be reduced by 90%.

- Above 3oC, large impacts begin to emerge for waterfowl habitat in the Prairie Pothole region. The collared lemming range is reduced by 80%, very large reductions are projected for Arctic sea ice cover particularly in summer which is likely to further endanger polar bears. Extinction of the Golden Bower bird is predicted in this temperature range. In Mexico very severe range losses for many animals are projected, as is the case also in South Africa, with Kruger national park projected to lose two thirds of the animals studied. The likelihood of the impacts identified above will continue to grow with higher temperatures.

Impacts on ecosystems

Figure 7 shows the impacts projected for a range of ecosystems including tropical forests, alpine systems in Australia and Europe, the Fynbos and Succulent Karoo in South Africa and, in the marine domain, coral reefs. With the information in Table 5, one may find the following conclusions:

- Between present temperatures and a 1^{o}C increase, three ecosystems appear to be moving into a high risk zone - highland tropical forests in Queensland, Australia, the Succulent Karoo in South Africa and coral reefs. Increased fire frequency and pest outbreaks may cause disturbance in boreal forests and other ecosystems.

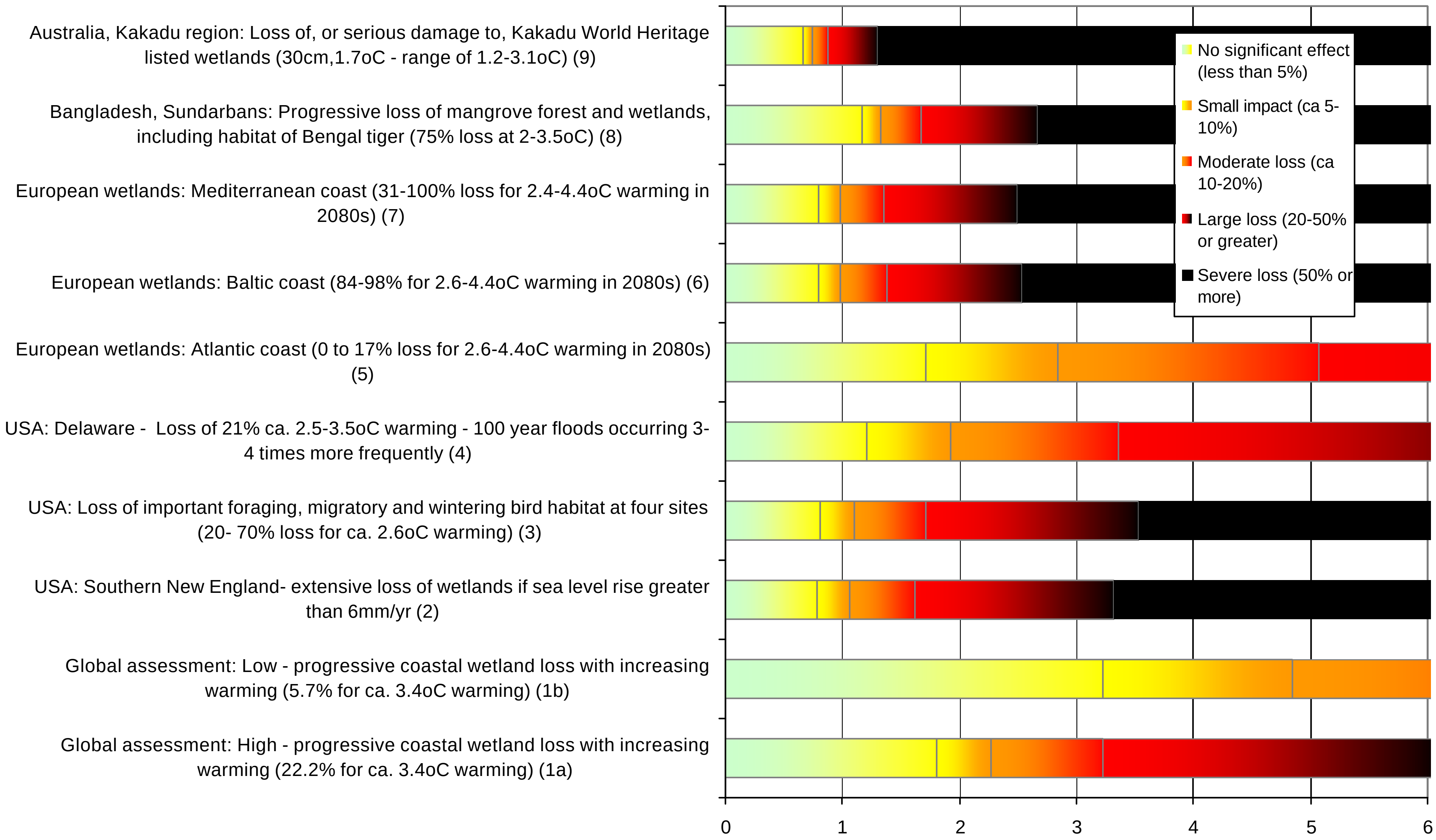
- Between 1-2^{o}C the Australian highland tropical forest, the Succulent Karoo biodiversity hot spot, coral reef ecosystems and some Arctic and alpine ecosystems are likely to suffer large or severe damage. The Fynbos will experience increased losses. Coral reef bleaching will likely become much more frequent, with slow or no recover, particularly in the Indian Ocean south of the equator. Australian highland tropical forest types, which are home to many endemic vertebrates, are projected to halve in area in this range. The Australian alpine zone is likely to suffer moderate to large losses. The substantial loss of

Arctic sea ice likely to occur will harm ice dependent species such as the polar bears and walrus. Increased frequency of fire and insect pest disturbance is likely to cause increasing problems for ecoystems and species in the Mediterranean region. Moderate to large losses of boreal forest in China can be expected. Moderate shifts in the range of European plants can be expected and in Australia moderate to large number of Eucalypts may be outside out of their climatic range.

- Between 2-3°C coral reefs are projected to bleach annually in a number of reef locations. At the upper end of this temperature band, the risk of eliminating the Succulent Karoo and its 2800 endemic plants is very high. Moderate to large reductions in the Fynbos can be expected, with the risk of significant extinctions. In the highland tropical forests of northeastern Australia “catastrophic loss” or rainforest vertebrates has been predicted Australian mainland alpine ecosystems are likely to be on the edge of disappearance. European alpine systems will at or above their anticipated tolerable limits of warming with some vulnerable species close to extinction. Severe loss of boreal forest in China is projected and large and adverse changes are also projected for many systems on the Tibetan plateau. Large shifts in the range of European plants seem likely and a large number of Eucalypt species may expect to lie outside of their present climatic range. Moderate to large effects are projected for Arctic ecosystems and boreal forests.

  Within this temperature range there is a likelihood of the Amazon forest suffering potentially irreversible damage leading to its collapse.

Figure 5 - Impacts on Coastal Wetlands



Notes: All examples are described in more detail in Table 5 - Ecosystem Impacts.

(1a) Global assessment: Based on the Nicholls *et al.*(1999) assessment using the high estimate of wetland loss (22.2% in 2100 for around a 3.4^{o}C warming). A linear extrapolation used to calculate 50% loss, which is likely to very much overestimate the temperature at which this would occur.

(1b) Global assessment: As above but for low estimates (5.7% loss by 2100) with linear extrapolation to 50%, which is likely to radically underestimate the at which this would occur.

(2) USA, southern New England: Based on Donnelly and Bertness (2001b) with assumption that a 5^{o}C increase (3-5oC range) by 2100 is associated with a 6mm/yr increase in sea level rise and an 80% (extensive) loss of wetlands.

(3) USA, migratory bird habitat: Based on Galbraith *et al.* (2002). The graph shown is for the average range of losses at the four sites that lose intertidal habitat for all warming and sea level rise scenarios - Willapa Bay, Humboldt Bay and northern and southern San Francisco Bay. The average losses at these sites in 2100 for the 2.6oC scenario is 44 % (range 26% to 70%) and for 5.3oC is 79% (range 61% to 91%). The latter point is used to scale the average losses with temperature, which increases the temperature sligtly for a given loss compared to the 2.6oC scenario. The Delaware bay site loses 57% of intertidal habitat for the 2.6oC (34 cm sea level rise) but gains 20% in the 5.3oC (77cm sea level rise scenario). Whilst the Bolivar flats site loses significantly by the 2050s for both scenarios (38-81%) it gains by the 2100s for both scenarios.

(4) USA, Delaware: Based on Najjar *et al.* (2000) assuming 21% loss at 3.5oC warming with linear extrapolation to 50%. A linear extrapolation used to calculate 50% loss, which is likely to very much overestimate the temperature at which this would occur.

(5) European wetlands - Atlantic coast: Based on IPCC WGII TAR Table 13-4 which is based new runs using the models described by Nicholls *et al.*(1999) with a linear extrapolation of the high range 17% loss with 4.4^{o}C warming to higher loss rates. This is likely to very much overestimate the temperature at which this would occur.

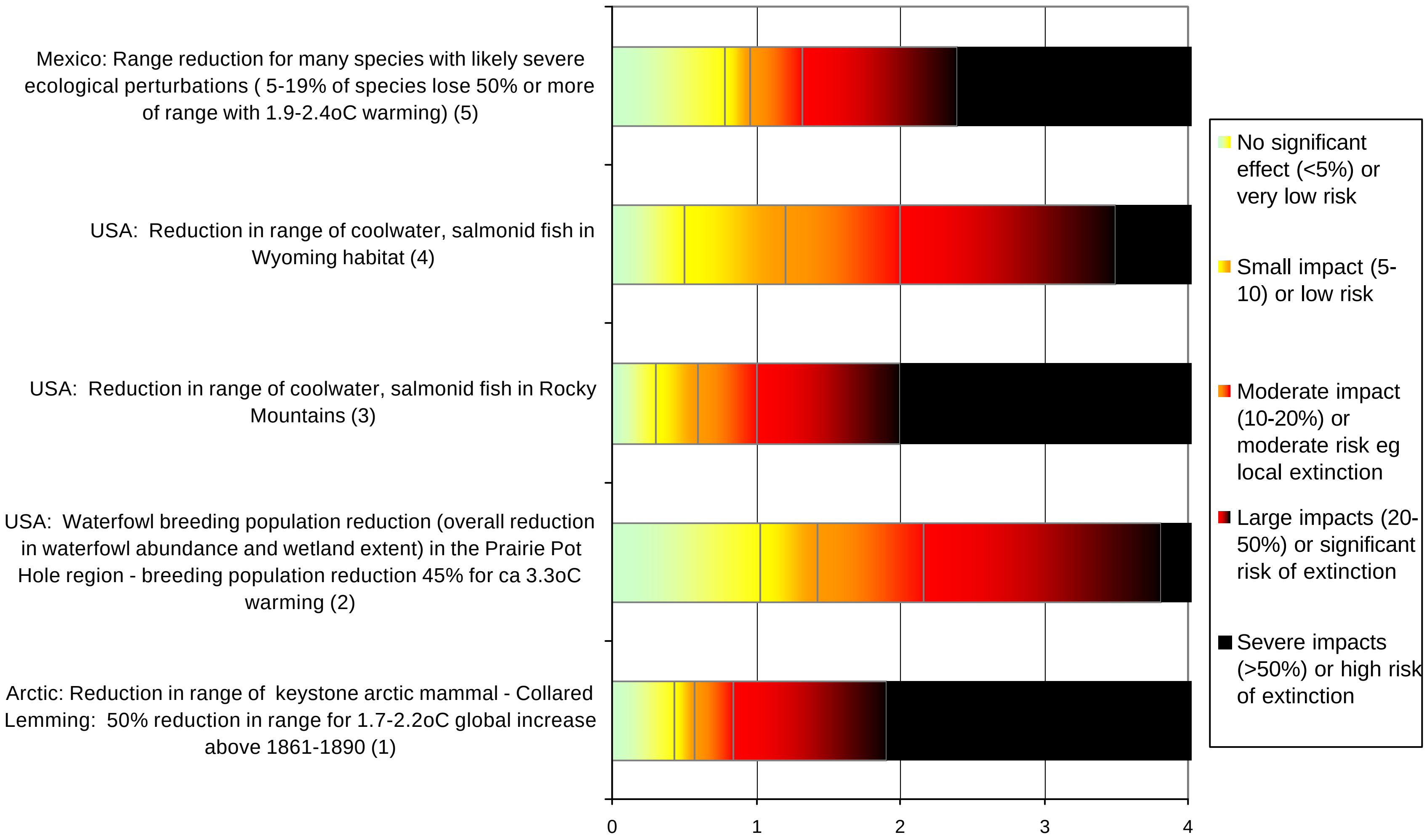
(6) European wetlands- Baltic coast: As above with linear extrapolation of high range 98% loss with 4.4^{o}C warming.

(7) European wetlands- Mediterranean coast: As above with a linear extrapolation of high range 100% loss with 4.4^{o}C warming.

(8) Bangladesh, Sundarbans: Based on Qureshi and Hobbie (1994) and Smith *et al.* (1998) with sea level rise and temperature relationship (for 2100) drawn from Hulme *et al*. (1999b). This produces very similar results to an estimate based on "average" model characteristics. Some models project higher sea level rise and others lower. Assumed relationship is 15% loss for 1.5oC (range 1-1.5oC) and 75% loss 3.5oC (range 2-3.5oC).

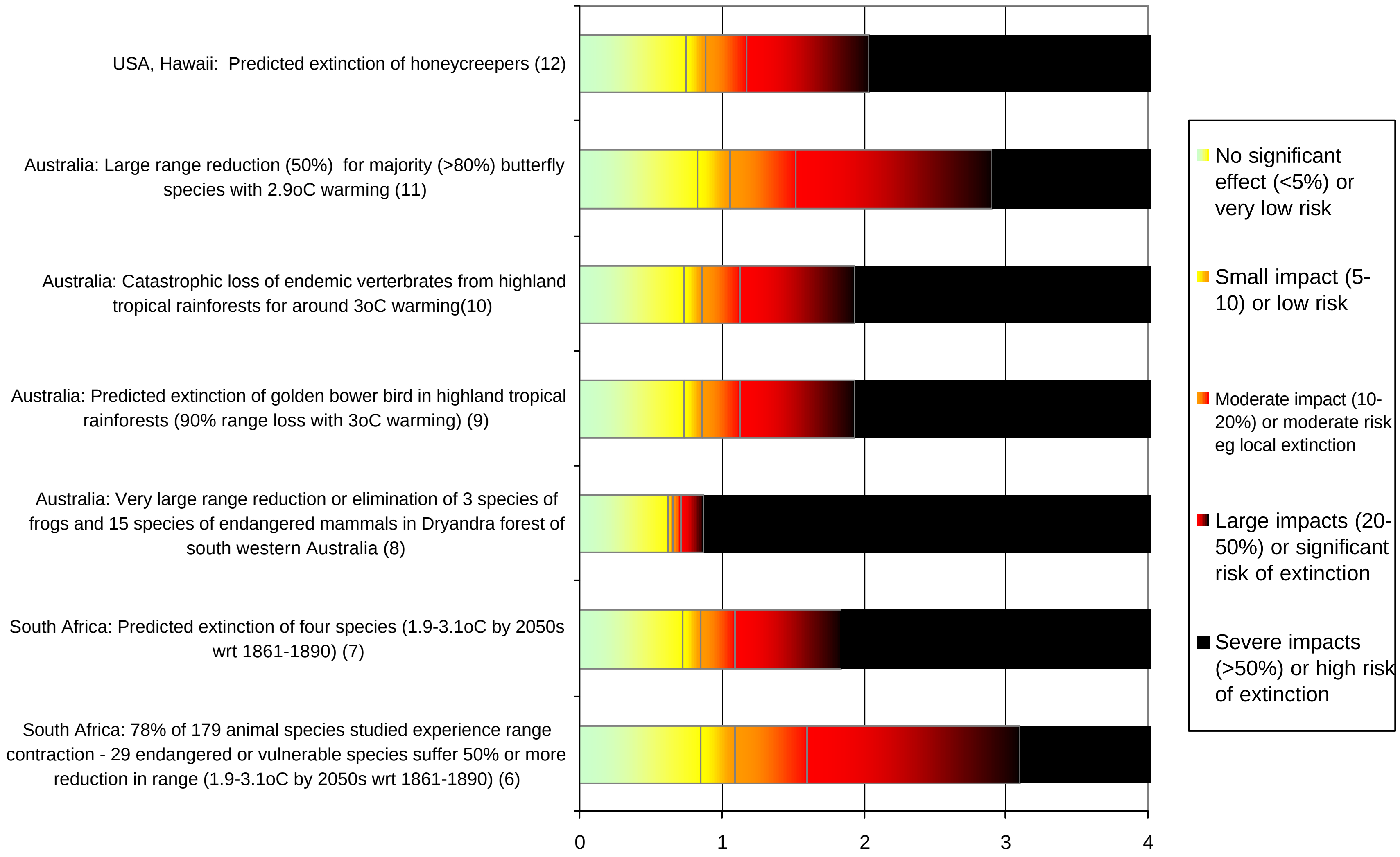
(9) Australia, Kakadu region: This estimate is highly uncertain. In the WGII TAR report Gitay *et al.* (2001) assert that the wetlands "could be all but displaced if predicted sea-level rises of 10–30 cm by 2030 occur and are associated with changes in rainfall in the catchment and tidal/storm surges" (p308). Here it is assumed that a 30cm sea level rise displaces 80% of the wetlands and that the sea level rise vs. temperature relationship is drawn from Hulme *et al.* (1999b) from the HadCM2 and HadCM3. Note that the estimate range from recent models is 1.2-3.1oC for a 30cm sea level rise.

Figure 6 – Impacts on Animal Species



See notes below:

Figure 6 **– Impacts on Animal Species continued:**



See notes below:

Notes: See Table 5 for more details

(1) Canadian Arctic, collared lemming: Based on data in Kerr and Packer (1998) with conversion of local temperatures to global mean based on a range of the current AOGCMs; mid-range used. Interpolation is used to estimate range reductions based on data in Kerr and Packer (1998).

(2) USA, waterfowl population Prairie Pot Hole Region: Based on data in Sorenson *et al*. (1998) with interpolation of data.

(3) USA, reduction of Salmonid fish habitat in Rocky Mountains: Based on data in Keleher and Rahel (1996) with extrapolations to 5% and 10% reductions. June, July, August temperatures 'upscaled' to global by associating projected JJA temperatures from a range of GCMs for the USA with global mean temperatures using MAGICC/SCENGEN. This is obviously quite uncertain given that temperature changes in the region are likely to be quite different from the USA average, with mountainous regions likely to experience amplification of trends for the continental averages.

(4) USA, reduction of Salmonid fish habitat in Wyoming: Based on data in Keleher and Rahel (1996) with extrapolations to 50% reduction. Upscaling of temperatures as in (3).

(5) Mexico: Highly indicative interpretation of results of Peterson et al. (2002) for range reductions. The 50% range reduction level is associated with the upper end of their warming scenario, which corresponds to 2.4^{o}C warming above 1861-1890 and this range reduction applies to up to 19% of the entire Mexican fauna. Between present temperatures and 2.4^{o}C a linear scaling is used here. Note that there is projected to be a severe risk of extinction for up to several tens of fauna species (0-2.4% of species lose 90% of range for 1.9-2.4^{o}C warming).

(6) South Africa, range reductions of large number of animals: Highly indicative only, interpretation of results of Erasmus *et al*. (2002) for range reductions in the 29 endangered species projected to experience 50% or more range reductions with a warming of 2.4^{o}C (1.9-3.1oC range) (above 1861-1890). The scale assumes that a 50% reduction in the range of these species occurs with 3.1^{o}C. Lower reductions are linearly scaled from 1990 temperatures.

(7) South Africa, predicted extinctions: Highly indicative only interpretation of results of Erasmus *et al*. (2002) for extinctions projected for a 2.4^{o}C increase (1.9-3.1oC range). The scale used assumes that there is a 100% chance of extinction with a 3.1^{o}C increase, zero probability at current temperatures, and the likelihood of extinction increase linearly.

(8) Australia, south west Dryandra forest: Based on Pouliquen-Young and Newman (1999) as cited by Gitay et al. (2001). Assumed that "very large" range reduction meant a 90% reduction, that the loss of range scale was linear for the present climate to a warming of 1.1^{o}C (above 1861-1890), and that 90% reduction occurs at 1.1^{o}C.

(9) Australia, predicted extinction of Golden Bower bird of highland tropical forests, north east Queensland: Based on (Hilbert et al. 2003) and using range reduction of 90% with a 3oC warming and linear interpolation for range losses between 1990 (0.6oC and 0% range loss) and this level.

(10) Australia, "catastrophic" loss of endemic vertebrates from rainforest in highland tropical rainforests: Based on (Williams *et al*. 2003) and with similar scaling as above.

(11) Australia, large range reduction in range of butterfly species: Based in (Beaumont and Hughes 2002) with risk of large range reductions for large numbers of species linearly increasing from zero at 0.6oC to 50% loss for 80% of species at 2.9oC.

(12) USA, predicted extinction for honeycreepers in montane forests of Hawaii: Based on (Benning *et al*. 2002) with risk of extinction to 90% at 3.2oC

Figure 7 – Impacts on Ecosystems

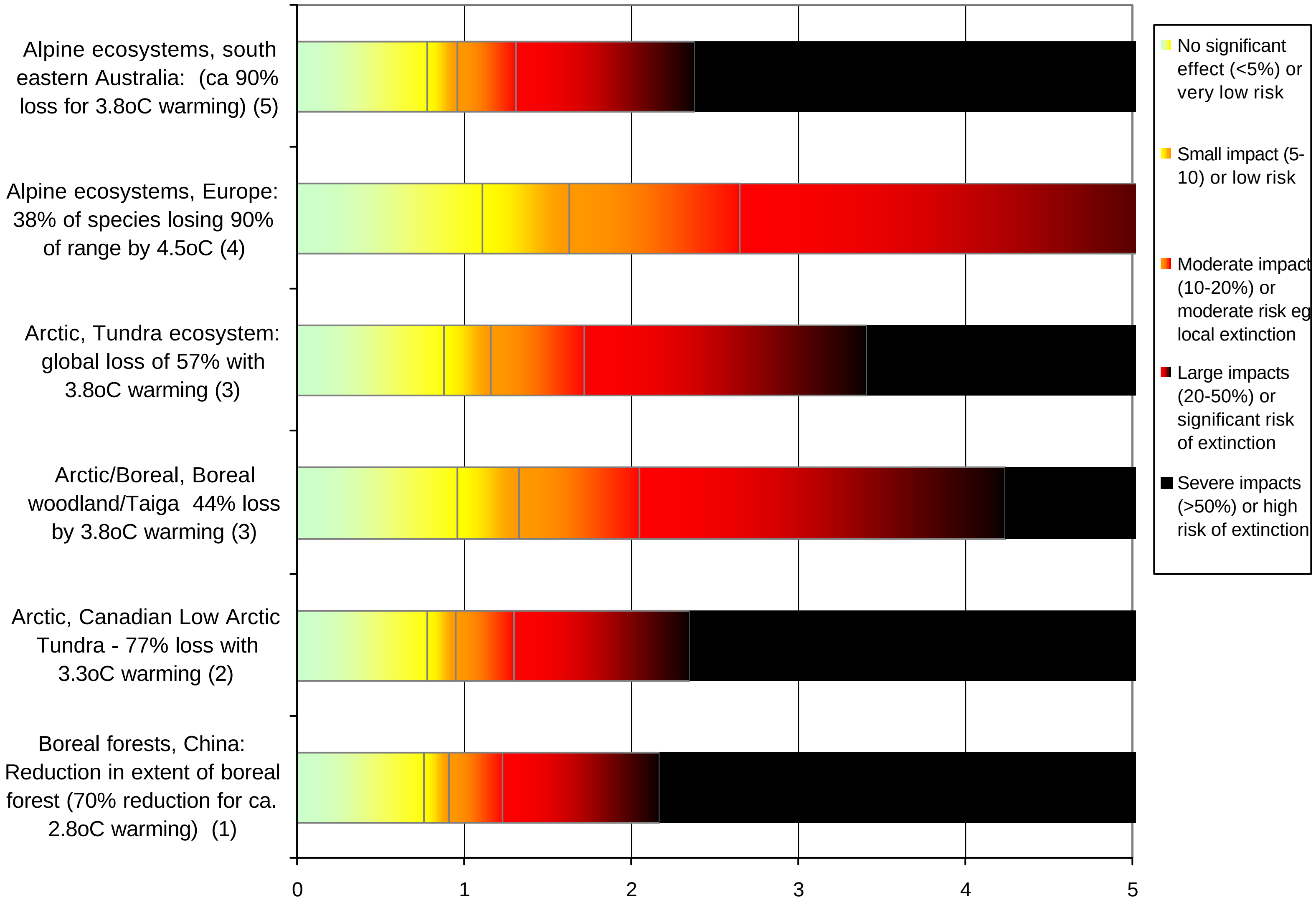
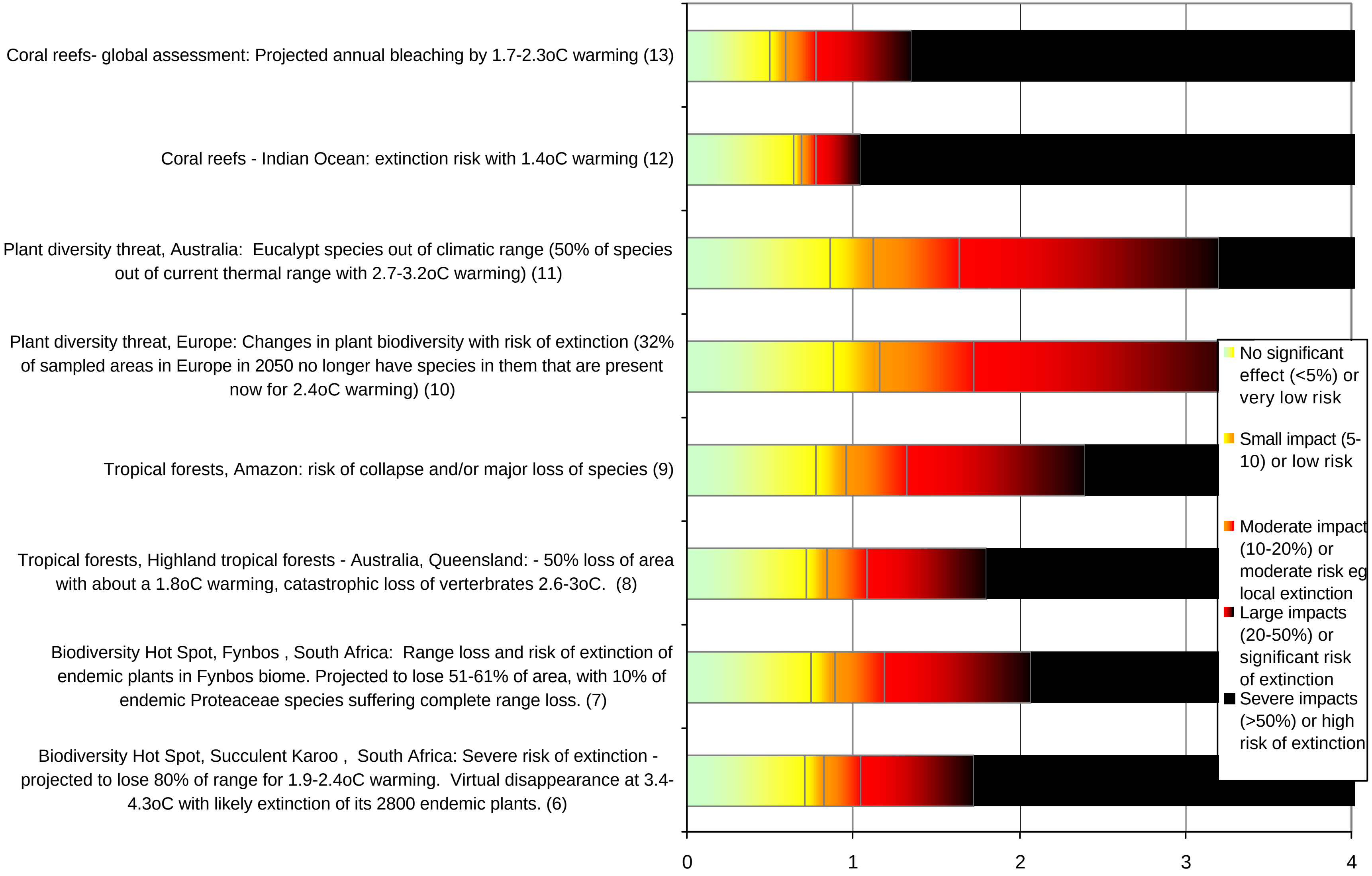


Figure 7 **– Impacts on Ecosystems continued:**



Notes: Details of each example are to be found in Table 5 - Ecosystem Impacts.

(1) Boreal forests, China: Based on Ni (2001) with linear scaling of loss of boreal forest in China with temperature.

(2) Arctic, Canadian Low Arctic Tundra: Loss of area is 77% with 3.3oC warming based on (Malcolm *et al*. 2002b) and linearly interpolated from zero at 0.6oC.

(3) Arctic/Boreal, Boreal woodland/Taiga and Arctic Tundra: Loss of ecosystems respectively 44% and 57% with 3.8oC warming and scaled linearly from zero at 0.6oC warming. Based on (Neilson *et al*. 1997)

(4) Alpine ecosystems, Europe: Highly indicative measure of risk only. Scale is percentage of alpine species losing 90% of their range with linear scaling of the estimated 38% losing this level with a warming of about 4.7^{o}C (range 3.3-4.7°C). This is done only to provide a visual picture of increasing risk with temperature, which is one of the main findings of the literature for this region (see Table 5 - Ecosystem Impacts).

(5) Alpine ecosystems, south eastern Australia: Assumes 90% reduction with a warming of 3.8^{o}C (above 1861-1890) with linear scaling of area loss from present climate. Busby (1988) found that the alpine zone would be confined to only 6 peaks for a warming of 1.7-3.8^{o}C.

(6) Biodiversity Hot Spot, Succulent Karoo , South Africa: Based on Midgley and Rutherford at http://www.nbi.ac.za/frames/researchfram.htm. The scale is likelihood of extinction of the 2800 plants endemic to the Succulent Karoo ecosystem, where it is assumed that the systems will no longer exist with 100% certainty with an increase of 2.4^{o}C and that the likelihood of extinction scales linearly upward from zero at current temperatures.

(7) Biodiversity Hot Spot, Fynbos , South Africa: Based on Midgley *et al*. (2002) and linear scaling loss of the area of Fynbos with temperature from zero at present up to 61% loss of area with a 2.4^{o}C increase (above 1861-1890). Ten percent of endemic Proteaceae species are projected to suffer complete loss of range, and hence are also very likely to become extinct with a 51-61% area loss in Fynbos.

(8) Tropical forests, Highland tropical forests - Australia, Queensland : Based on results of Ostendorf *et al*. (2001), Hilbert *et al*. (2001), Williams *et al*. (2003) and Hilbert *et al*. (2003) with linear scaling of area losses with local temperature increase. Across results from different assessments this produces fairly consistent estimates.

(9) Tropical forests, Amazon: This is speculative drawing on the work of Cowling *et al*. (2003) and Cox *et al*. (2003) and assuming that there is a 50% risk of collapse with a warming of 2.4oC. See discussion in Table 5 and footnote XX and Note (1) at the end of this table.

(10) Plant diversity threat, Europe: Based on Bakkenes *et al*. (2002) with scale being fraction of plant species occurring at present within a grid cell in Europe that no longer appear with given level of warming. Assumes linear scaling with temperature increase above the present. As such is indicative only of increasing risk with temperature, the risk being that of extinction or severe range reduction. The absence of plants from a grid cell in 2050 does not imply that the species is globally extinct, only that it is no longer climatically suited to that region. The higher the fraction of species displaced in the model is a measure of the ecological dislocation caused by rapid warming and for some species is indicative of the rising level of extinction risk.

(11) Plant diversity threat, Australia: Based on Hughes *et al*. (1996). Scaled number of species out of climatic range with temperature above present.

(12) Coral reefs - Indian Ocean: Based on the work of who predicts extinction of reef sites in the southern Indian Ocean for warming in the range 0.9-1.4°C. It is assumed that there is a 90% chance of extinction at a temperature increase of 1.4oC.

(13) Coral reefs - global assessment: Based on results of Hoegh-Guldberg (1999). For both models used and all reefs studied, annual bleaching occurred by 2040s. Scale is chance of a major bleaching occurring in a decadal period e.g. 10% corresponds to 1 year per decade, 50% to five year out of 10 and 100% to annual bleaching. Scaling is from 0.4^{o}C above 1861-1890 as unusual bleaching began in the 1980s with annual bleaching occurring at 2.3^{o}C above 1861-1890.

Table 5 - Ecosystem Impacts

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Arctic ecosystems	Arctis	Major range reduction for a keystone arctic species, the collared lemming, with likely large negative impacts on Arctic ecosystems. Range reduction 50% 80%	1.7-2.2°C[7] 3.3-4.5°C[8]	The Collared Lemming (Dicrostonyx groenlandicus) is basic part of the food chain and a major food source for a number of predators – birds and mammals (Kerr and Packer 1998). Twenty-five mammals in Canada have their northward range movement limited by the Arctic ocean (See also TAR WGII Section 5.4.3.2). The temperature scenarios used were for a 2, 4 and 6oC local mean annual warming[9]. The percentage reductions in range cited are interpolated from the data in Table II of Kerr and Packer (1998). Temperatures in the Arctic region are known to be warming rapidly, with the rate of warming appearing to increase recently	Arctic mammal distribution is closely correlated with temperature and a number of mammals are adapted to survive in colder climates. Warming is projected to lead to their northward migration, assuming habitat availability. The Arctic ocean places a limit on the extent of this possibility.
Arctic ecosystems	Arctis	Substantial reduction of sea ice area and possible complete loss of summer sea ice in the Arctic ocean by end of 21st century, or earlier depending on scenario, with major implications for ice dependent species. Reduction in annual ice cover 15-20% 40-50% Mid summer ice cover reduction 50%	2°C 4°C 1.5-2°C	Sea ice area, extent and thickness have been declining in recent decades, with the perennial cover being lost at a rate of 9% per annum over the period 1978-2000 (Comiso 2002b). A strong correlation has been observed between warming and ice losses (Comiso 2002a). Record losses were reported by for sea extent and area in 2002 (Serreze *et al.* 2003). The HADCM3 model predicts a further 15-20% (40-50%) reduction in annual ice cover for a 2°C (4°C) increase in global mean temperature above 1861-1890 (Gregory *et al.* 2002). A much larger proportional reduction in summer ice is projected, with a loss of 50% by the 2050s corresponding to a global mean warming of around 1.5-2°C (Gregory *et al.* 2002). Johannessen *et al.* (2002), using ECHAM4 and HADCM3 with a new sea ice observed data set, predict for summer a "predominantly ice-free Arctic Ocean" by the end of the 21st century. Their mid summer ice loss projections of 30-60% by the 2050s, depending on scenario, are similar to those of Gregory *et al.* (2002). Amongst other effects this could be expected to have profound implications for arctic and sub arctic marine biodiversity and would affect, almost certainly negatively, polar bear populations (Stirling *et al.* 1999; Stirling 2000).	Arctic sea ice responds rapidly to warming on a timescale of years rather than decades. Polar bears are dependent on sea ice for hunting and a loss of sea ice is very likely to reduce the viability of bear populations (Stirling *et al.* 1999). An ice free Arctic ocean in summer would also lead to very large changes in the marine biota with negative consequences for ice dependent species.

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[6] Above 1861-1890 average unless otherwise stated. See Appendix on temperature scale.

[7] Local temperature increase scenarios are converted to global mean using average of nine recent GCMs upscaled from the Canadian Arctic region using SCENGEN. The scaling used is 1.86°C local increase per degree of global mean increase calculated with the A1B-MESSAGE scenario, with the range set by the inter-model standard deviation of 0.3°C/°C. Using the full range of models available in SCENGEN produces a lower scaling, however examination of the scaling for the higher Arctic region of Canada, which is what would apply under the range reductions cited in the table, indicates a higher scaling factor (2.07 °C/°C with inter-model standard deviation of 0.42°C/°C). This would tend to slightly lower the upper end of the global temperature range (e.g. the range would be 1.5-2.1°C for a 50% loss and 2.9-4.2°C for an 80% loss.

[8] The maximum local warming of 6°C produced a range reduction of 78%. The local temperature increase corresponding to an 80% reduction is estimated from a 2nd order polynomial regression on the data in Table II of Kerr and Packer (1998). A linear extrapolation would produce a slightly lower temperature increase.

[9] The baseline for this warming is assumed to be 1961-1990 as the observed distribution of the mammals was regressed against historical means annual temperatures.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Arctic ecosystems	Arctis – global assessment	Global loss of area of tundra ecosystem 40-57%	1.3-3.8°C [10]	Large losses of tundra ecosystem are projected for a range of future climate scenarios taking into account the effects of CO_2 increases. Projected ecosystem area losses are drawn from the assessment of Neilson *et al.* (1997) prepared for the IPCC Regional Impacts report[11]. Here only the results from climate models and scenarios used in the IPCC Second Assessment Report (SAR) are cited. Results for the scenarios drawn from climate models reviews in the IPCC First Assessment Report (FAR) are not used here, as the models are older and less reliable[12].	Warming causes the northward migration of Tundra and other high latitude ecosystems. The tundra in particular has its migration limited by the Arctic ocean. The rate of required migration is found to be higher than known from past climatic changes.
Arctic ecosystems	Arctis - Canada	Large reductions in tundra and taiga projected. Estimated future rate of change of climate exceeds known past changes. Loss of area of Canadian Low Arctic Tundra 75-77%[13] (19% loss of species estimated)	2.2-3.3°C [14]	Malcolm *et al.* (2002b) estimated migration rates for biomes globally in response to climate change using several GCMs and two vegetation models. They found that high latitude and Arctic ecosystems (boreal forests, taiga) needed very high migration rates to keep up with projected rates of climate change. Tundra systems in particular experienced large area losses in this assessment. In a related study, Malcolm *et al.* (2002a) found that several high latitude and arctic ecosystems were particularly vulnerable to rapid change under each of the models examined[15]. These systems included the Canadian Low Arctic tundra, Boreal Taiga, East Siberian Taiga, Russian coastal tundra, as well as several boreal forests. Species loss in response to the loss of area of ecosystems was estimated using established species-area relationships. Such estimates may be conservative (Seabloom *et al.* 2002). For the Canadian Low Arctic tundra, where an average 76% area loss was projected, the corresponding species loss was estimated to be around 19%.	Warming causes the northward migration of Tundra and other high latitude ecosystems. The tundra in particular has its migration limited by the Arctic ocean. The rate of required migration is found to be higher than known from past climatic changes.

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[10] Based on the transient scenarios used by Neilson *et al.* (1997), which were with reference to 1961-1990 and are described as having global mean surface temperatures increases in the range 1-3.5°C by the time of CO2 doubling.

[11] See Table C-1 in Neilson *et al.* (1997) for the full range of results.

12 Some literature uses the full range including the IPCC First Assessment Report (FAR) scenarios, which in general produce somewhat different results (see Table 2 of Kittel *et al.* (2000)) showing a reduction in area of 40 to 67% for the tundra)

[13] Malcolm *et al.* (2002b) for range of BIOME3 and MAPSS projections under the climate scenarios assumed.

14 Malcolm *et al.* (2002b) base their projections on HadCM2 scenarios with and without sulphur and on the ECHAM4 scenario without sulphur for the period of 2070-2099. These scenarios have a global warming range, relative to 1961-1990 of 1.9-3.0°C, to which added the warming from 1861-1890 of around 0.3°C to the base period (see their footnote 2 for further details).

[15] The global vegetation models MAPSS and BIOME3 were used to model the equilibrium distribution of generalized plant types for the present and future projected climates. At larger spatial scales these kinds of models perform reasonably well (Pearson and Dawson 2003)

[15] Differences between present distributions and projected future distributions were analysed to estimate the rate of migration required for biome types to keep pace with the projected climate changes. Migration rates were computed taking account physical barriers and human land use. A general pattern observed was a "front" of very rapid migration rates at higher northern latitudes, where climate changes are expected to be most rapid. BIOME3 and MAPSS use ecological, hydrological and physiological processes to describe the distribution of species.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Boreal Forests	Eurasia and North America	Significant losses of boreal forests and associated carbon stocks projected. Releases of carbon 60-90GtC after 100 years	2.8°C [16]	Kirilenko and Solomon (1998) use a transient scenario to assess the effects of climate changes on a number of major ecosystem types taking into account different rates of potential plant migration and also agricultural land demand. They find a large release of carbon from this system due to transient effects, of the order of 60-90 GtC after 100 years, using average migration rates and taking into account agriculture. Kirilenko *et al.* (2000) examine the implications of changes in the variability of climate for the boreal forests, finding that increased variability slightly reduces the amount of forest loss.	Whereas tree dieback and loss can occur very quickly due to disturbances, regrowth is significantly slower (Kirilenko and Solomon 1998; Kirilenko *et al*. 2000). Several model projections for changes in high latitude vegetation and confirm that these ecosystems will be far from equilibrium in the future due to the rapid climate change (Brovkin *et al*. 2003). The changes are likely to be abrupt and there is a significant positive feedback to climate warming with the changes in vegetation and snow cover projected.
Boreal Forests	Eurasia and North America	Losses of boreal forest and woodlands Boreal forests 36% - 10% increase Boreal woodland/Taiga 36-44%	1.3-3.8°C [10] 1.3-3.8°C[10]	Using the BIOME3 and MAPSS equilibrium vegetation models large potential losses of total area of boreal forest and woodland are projected (Neilson *et al.* 1997). Changes to the boreal forests (not including woodland/Taiga) are in the range of a 36% decrease to a 16% increase, whereas the boreal woodland/Taiga has a projected decrease in the range 36% to 44%[17]. Climatic pressure on the boreal woodland/Taiga is clear also from the work of Malcolm *et al.* (2002a). In this latter work, which is based around the same models but a narrow range of climate scenarios (see footnote 14), a number of Taiga regions are identified as being particularly and fairly consistently at risk. Using the LPJ dynamic vegetation model Kittel *et al*. (2000) find the largest rates of change at the present southern limits of the boreal forests in central and western Eurasia .	See above
Boreal Forests	China	Reduction of boreal forest area in China. 70%	2.8°C [18]	Large reductions in the area of boreal forests in China are projected using BIOME3 (Ni 2002). Ni found "dramatic changes in geographic patterns, with 70% reduction in area and disappearance of almost (sic) boreal forests in northeast China." Climate projections from the Hadley model (Johns *et al.* 1997) for the period 2070-2099[18] were used relative to a 1931-1960 base period, to estimate changes in ecosystems and carbon storage in China. The atmospheric CO_2 in the model was increased to 500 ppmv in 2070-2099 from 340 ppmv in the base period. A reduction in carbon storage in China's boreal forests is projected, however other work by (Ni J 2001) and Ni *et al.* (2000) show that carbon storage should increase in China as a whole.	Warming causes poleward shift of many ecosystems and the boreal forests experiences pronounced pressure in this direction.[19]

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[16] Kirilenko and Solomon (1998) use projected climate change from a CO2 doubling scenario of Manabe *et al*. (1992). Table B-1 of the IPCC Special Report on the Regional Impacts of Climate Change (Watson *et al.* 1998) indicates that at the time of CO2 doubling, around 2050, the Manabe *et al*. (1991; 1992)scenario projects a warming of 2.2°C, with respect to 1990.

[17] See Table C-1 of Neilson *et al.* (1997) and using only the IPCC Second Assessment Report scenarios for climate changes at the time of CO2 doubling. The results for the scenarios drawn from First Assessment Report are not used.

[18] Ensemble average of the HadCM2 scenarios forced with IPCC IS92a emissions including the effects of sulphur emissions for the period 2070-2099. Data from the IPCC DDC website.

[19] For strengths and weakness of bioclimatic envelope models see Footnote 3.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Alpine and mountain	Europe - Alps	Large range decrease for alpine species. Percentage of species with greater than 90% range loss: 3.2% 17.7% 38%	1.5-2°C [20] 2.4-3.3°C[21] 3.3-4.7°C[22]	Three local warming scenarios (1.5, 3, and 4.5°C) with respect to the present climate (assumed to be 1990, as plant distributions are calibrated on the current climate) show a number of impacts. A few plant extinctions (1-3) are projected in the study area (Guisan and Theurillat 2000). Perhaps more importantly the study shows very large range decreases (90%) for 3.2%, 17.7% and 38% of species for each of the three temperature scenarios respectively (see Table 1 of Guisan and Theurillat (2000)). Whilst the authors caution that these are not to be taken as accurate predictions their results do provide a basis for assessing the major likely direction of changes.	The highest alpine species, whose ranges are restricted to the alpine zone, would experience a reduction in suitable bioclimatic zone due to warming and topography of mountains, where suitable physical habitat area declines rapidly with altitude.
Alpine and mountain	Europe – Alps	Risk of extinction of high alpine and nival plant species. Likely tolerable limit for most alpine and nival species but could be exacerbated by land use changes in many areas. Disappearance of some categories of vulnerable plants and substantial further range reduction of many other species.	1.2-2.4°C[23] 2.4-4.3°C[24]	The IPCC TAR found, based in part on the work of Theurillat and Guisan (2001), that a local warming of 3-4°C was most likely not to be within the range species could tolerate.[25] The IPCC TAR also found that in the European Alps the literature suggested that most alpine and nival species seem likely to able to cope with a local warming of 1-2°C. Some isolated orophytes living at the tops of mountains and some nival species are projected to lose area or disappear. By far the greatest negative ecological impacts appear to be in the upper elevations or true alpine zone. Theurillat and Guisan (2001) argue that species restricted to low mountain tops or whose range is limited by soil and other factors to small areas are likely to be "severely endangered by extinction." They argue that whilst the maintenance of traditional land use is essential to reduce the effects of warming, it is likely that other land uses will reduce the resilience of the alpine system to climate change.	High Alpine and nival species are restricted in range and warming will reduce that range. Where species are endemic to a mountain or range of mountains and bioclimatic zone rises then there is likely to be substantial pressure on vulnerable species. Suitable habitat declines with altitude.
Alpine mountain	Asia – Tibetan Plateau	Large scale changes to environment of Tibetan plateau and acceleration of desertification.	2.8°C[18]	A large reduction in the temperate desert, alpine steppe, desert, and ice/polar desert are projected using the equilibrium vegetation model BIOME3 driven by a climate scenario derived with the HadCM2 model (Ni 2000). With the projected warming it can also be expected that there will be a large increase in the cold-temperate conifer forest, temperate shrubland/meadows, and temperate steppe, along with a general north-westward shift of all vegetation zones. Continuous permafrost would mostly disappear. With the expansion of permafrost free	Warming of the high altitude plateau of Tibet causes a reduction in the coldest bioclimatic type and in permafrost. There are special high attitude biomes that would be substantially reduced with warming. Other ecosystems would expand.

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[20] A 1.5°C local temperature increase converted to global mean using the average of nine recent GCMs downscaled to the European Alpine region using SCENGEN. The regional to global scaling used is 1.39°C/°C with the range set by the inter-model standard deviation of 0.3°C/°C. The scaling factors using all 17 models in SCENGEN are not very different from the 9 model estimate. The base period is assumed to be 1990 hence 0.6°C is added to the global temperature to estimate the increase with respect to 1861-1890.

[21] A 3°C local temperature increase converted as in footnote 20 to a global mean increase.

[22] A 4.5°C local temperature increase converted as in footnote 20 to a global mean increase.

[23] A 1-2°C local temperature increase converted to the global mean as in footnote 20.

[24] A 3-4°C local temperature increase converted to the global mean as in footnote 20

25 See IPCC TAR WGII TAR 13.2.1.4. Mountains and Subarctic Environments http://www.grida.no/climate/ipcc_tar/wg2/500.htm (Kundzewicz *et al*. 2001).

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
				regions this would accelerate desertification of the Tibetan plateau (Ni 2000). The scenario used by Ni (2000) is based on the HadCM2 model with an emissions scenario that includes sulphur and was constructed with a base period of 1931-1960 compared with 2070-2099. The effects of increased CO_2 concentrations were accounted for, with a CO_2 level of 500 ppmv being used in the projection period years and 340 ppmv in the base period.	
Alpine mountain	Australia	Major reduction and ultimate loss of Alpine zone in southeastern Australia and consequent loss of endemic species.		The alpine zone in southeastern Australia appears to be one of the more vulnerable ecosystems. The IPCC TAR assessment for Australia (IPCC TAR WGII Chapter 12 (Pittock *et al.* 2001)) found that: "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." This confirmed the findings of the 1998 IPCC Regional Impacts assessment report, which found that the Australian alpine region was one of the most vulnerable systems in the region. This risk was first identified in 1988 by Busby who estimated that a warming of around 2-3°C in southern Australia would result in the confinement of the alpine zone to only six peaks, with a "dramatic effect on the survival of the majority of the present alpine species". More recent bioclimatic modelling by (Brereton *et al.* 1995) confirmed the overall assessment of Busby (1988). Based on lapse rate considerations, there is a substantial risk that, for a warming above about 3°C over 1990 levels, the northern Alpine zone would no longer exist and that before this many of the endemic species to the Australian zone in this region would become extinct in this region (Hughes 2003).	The geography of this region is such that there is very limited scope to attitudinal migration. Using standard lower troposphere lapse rates the rise in the Alpine bioclimatic zone with temperature can be calculated with increasing mean temperature (Peters and Darling 1985). The present estimate is based on the geography of this Alpine region and its bioclimatic zonation. Much of the region is protected as a national park, hence land use pressures as such are not the main determinant of the future of this region.
		Confinement of the alpine bioclimatic zone to six peaks.	1.7-3.8°C[26]		
		Likely elimination of northern alpine bioclimatic zone	2.1-4.1°C[27]		
		Confinement to isolated mountain tops in Tasmania	4.0-8.1°C[28]		
Alpine mountain	Australia	Major reductions in snow area with negative impacts on snow dependent species.		Projections for the Australian Alps indicate a major loss of snow coverage with warming (Whetton *et al.* 1996).[31] The most recent scenarios for southern Australia are warmer than the 1996 scenarios - 0.6-3.4°C by 2030 as opposed to 0.3-1.3°C and 0.8-5.2°C by 2070 as compared to 0.6-3.4°C (CSIRO 2001), indicating a larger loss of snow area.[32]	Projected climate change results in warming and changes in circulation which reduces snow precipitation and the period in which snow cover can be maintained,
		18-66%	0.9-1.9°C[29]		
		39-96%	1.2-4.0°C[30]		

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[26] Based on Busby (1988) assuming that the scenario used has a base period of 1975-1984 and that the local temperature increases of 2-3°C is with respect to this period. These regional temperature increases are scaled to an estimated corresponding global mean temperature increase using 0.985°C/°C with an inter-model standard deviation of 0.194°C/°C obtained using 9 recent models and the SCENGEN programme (REFS). Note that the regional definition over the Australian Alpine region using SCENGEN is very coarse. Choosing slightly different regions or using the full range of models in the SCENGEN utility does not change the range fundamentally.

[27] Estimate based on a lapse rate in the range of 0.6-0.8°C/100m and using Mt Kosciuszko at 2200m as the highest point in the northern alpine zone with the rise from the beginning of the Alpine zone at 1800 m in the 1980s to 2200m defining the local temperature increase required to eliminate the northern Alpine zone. The same regional to global scaling is used as in footnote 26. Note that using a scaling for a slightly narrower and more northerly region but still covering the Mt Kosciuszko area would reduce the range to 2-3.9°C.

[28] Estimate based on a lapse rate in the range of 0.6-0.8°C/100m and estimating rise of current Alpine zone in Tasmania, which starts at about 800m to 1500 metres, leaving a few peaks above this level. The regional downscaling used those for southeastern Australia from SCENGEN as these were most consistent with the CSIRO scenarios for southern Australia and Tasmania. The scaling used was 0.874 °C/°C with an inter-model standard deviation of 0.184 °C/°C. The grid cells available from SCENGEN over Tasmania are mostly ocean and may underestimate the warming locally in Tasmania. If that had been used the scaling used was 0.652°C/°C with an inter-model standard deviation of 0.192 °C/°C producing a range of warming from 5-12.2°C.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Alpine mountain	Australia	Endangerment and possible extinction of species. Likely extinction in the wild of the mountain pygmy possum due to complete loss of its bioclimatic zone.	1.2-1.7°C[33]	A number of vertebrates and plants are limited to the Alpine zone and require the seasonal occurrence of snow (Hughes 2003). Three mammals (dusky antechinus, broad-toothed rates and the mountain pygmy possum), whose abundance increases with altitude, are adversely affected by loss of snow (Green and Pickering 2002; Hughes 2003). The bioclimatic zone occupied by the highly endangered Mountain pygmy-possum (*Burramys parvus*) is estimated to be lost with a local warming of 1°C (Brereton *et al*. 1995). Invasion of the high plains of the Alpine zone with sub alpine, woody species would lead to a substantial change in the landscape. Distributions of trees are limited to be zones where the average temperature of the warmest month is greater than 10°C.	The Australian Alpine zone has a very limited altitudinal range, being essentially plateaus, and hence beyond a certain temperature increase, upwards altitudinal migration is impossible. The Pygmy possum (*Burramys parvus*) is limited to about 10km^2 of habitat. Given this situation climate change is clearly a longer-term pressure on this species, however there are intensive efforts being made to maintain this species *in situ*. Loss of snow cover would most likely mean, or at least contribute very strongly to, the extinction of the pygmy possum in the wild.
Alpine mountain	Australia	Large range reduction of the Alpine tree frog in Eastern Australia 51-89%	3.1-4.6°C[34]	The Alpine tree frog (*Litoria verreauxii alpina*) is one of the species threatened by climate change. Using a bioclimatic model BIOCLIM Brereton *et al.* (1995) estimated that a 3°C warming would reduce the frog's range by 51-89%[35]. The range of the Alpine tree frog is thought to be limited to several national parks (Kosciusko National Park; Namadgi National Park; Alpine and Buffalo National Parks) and some public forests[36]. Range losses have already occurred at lower Alpine plateaus such as Mt Baw Baw. Whilst drought has been linked to these losses, there is no final assessment of the causes of this range reduction. Management issues in public forests as well as in the protected areas mentioned above have a direct bearing on the species vulnerability. It is clear, however that climate change is likely to have a determining influence in the longer term.	Warming will reduce the frog's range according to estimates with a bioclimatic model. Land use change pressures occur but most of the present range lies within protected areas. Hence climate change is likely to put very strong adverse pressure on the species.

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[29] Original projections for 2030s are with respect to 1990 hence an offset of 0.6°C is added to obtain the range of increase wrt to 1861-1890.

30 Original projections for 2070s are with respect to 1990 hence an offset of 0.6°C is added to obtain the range of increase wrt to 1861-1890.

[31] See also CSIRO (1996). Note that the CSIRO has produced new scenarios (CSIRO 2001), which in general predict higher warming than the 1996 scenarios.

[32] New snow cover projections have been released recently (Hennessy *et al.* 2003) which project larger losses of snow cover than those shown here.

[33] The regional temperature increases of 1°C is scaled to an estimated corresponding global mean temperature increase using 0.874°C/°C with an inter-model standard deviation of 0.184°C/°C obtained using 9 recent models and the SCENGEN programme assuming that the baseline climate is 1961-1990. The 1989 CSIRO scenario used for this work was not available. If the baseline was 1990, then the global mean temperature increase above 1861-1890 would be 1.5-2°C.

[34] The regional temperature increases of 3°C is scaled to an estimated corresponding global mean temperature increase using 0.874°C/°C with an inter-model standard deviation of 0.184°C/°C obtained using 9 recent models and the SCENGEN programme assuming that the baseline climate is 1961-1990. The 1989 CSIRO scenario used for this work was not available. If the baseline were 1990, then the global mean temperature increase above 1861-1890 would be 3.9-4.6°C.

[35] Bioclimatic models such as BIOCLIM tend to overestimate species ranges (Hughes 2003).

36 See http://ea.gov.au/biodiversity/threatened/action/frogs/17.html.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Coastal Wetlands	Global	Progressive coastal wetland loss with increasing warming. 0-2.3%[37] 1.8-10.5%[38] 5.5-22.2%[39]	 1.4-1.5°C[40] 2.4°C 3.3-3.4°C	The greatest losses of coastal wetlands are projected in the Mediterranean and Baltic region, with large losses also in the Sundarbans (Nicholls *et al.* 1999). Significant losses on the Atlantic coast of Central and North America and the smaller islands of the Caribbean are also projected. The climate scenarios used in the study were the result of greenhouse gas only runs with the HadCM2 and the HadCM3 models forced by greenhouse gas emissions approximating the IS92a scenario, which produces a warming of around 3-3.1°C by the 2080s. Resulting sea level rise from these models was 40-41 cm by the 2080s relative to the 1961-1990 mean sea level (Hulme *et al.* 1999a).	Model based assessment of the vulnerability of each region to sea level rise taking into account local factors.
Coastal wetlands	Australia	Loss or serious damage to Kakadu World Heritage listed wetlands.	1.2-3.1°C[41]	The topography of the wetlands for the Kakadu regions appears to lead to an especially vulnerable situation. A sea level rise of 10-30 cm combined with rainfall changes and increased tidal surges is postulated to severely reduce the freshwater wetlands of this region. The authors of the ecosystem assessment in the IPCC TAR argue that these wetlands could "be all but displaced if predicted sea-level rises of 10–30 cm by 2030 occur and are associated with changes in rainfall in the catchment and tidal/storm surges" (Gitay *et al.* 2001) (WGII TAR Chapter 5, p 308). Associating these sea level increases with a global mean surface temperature change is difficult (see footnote 41). Sea level will result in saltwater intrusion and shoreline erosion, with the loss of some coastal mangroves (with colonization along creeks as the tidal zone expands), extensive loss of paperbark trees (*Melaleuca* spp.) in the wetland, and ultimately replacement of freshwater wetlands by saline mudflats (Eliot *et al.* 1999). These vegetation changes would results in adverse changes in the abundance of wildlife such as Magpie Geese and long-necked turtles, which are hunted by the aboriginal owners of Kakadu. Gitay *et al.* (2001) point to the loss of large areas of freshwater wetlands further to the west, in the Mary river, as a consequence of salt water intrusion (Mulrennan and Woodroffe 1998). The possibility that the processes that drive the vulnerability of the Kakadu wetlands to sea level rise could extend to much larger regions with similar low lying character in the monsoonal tropic is raised but not explored in the TAR.	The vulnerability of the wetlands of Kakadu, and of other river systems in the region, arises as these areas lie within 0.2-1.2m of high water level. The coast is largely mangroves with inland fringing salt flats of low productivity and diversity. Behind these lie low ridges that form a barrier to salt water intrusion onto the low lying flood plains, below the inland escarpment some 100km from the coast. Sea level rise is postulated to lead to the retreat of the mangrove zone and the inland spread of the tidal zones of the creeks of the region, penetrating into the freshwater zone (Gitay *et al.* 2001) and (Bayliss *et al.* 1997).

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[37] These results are for a sea level rise of about 12cm in the 2020s with respect to 1961-1990. The range is the highest and lowest estimates taking into account a number of factors and using the sea level rise scenarios from the HadCM2 and HadCM3 models – see Table 10 of Nicholls *et al.* (1999).

[38] These results are for a sea level rise of about 24-25cm in the 2050s with respect to 1961-1990.

[39] These results are for a sea level rise of about 40-41cm in the 2080s with respect to 1961-1990.

[40] See Table 1 of Hulme *et al.* (1999a) for an overview of the results of these scenarios.

[41] Estimated warming at the time of sea level rise of 10-30cm (above 1990) being reached based on HadCM2 projections (Hulme *et al.* 1999a). Note that associating sea level increases of 10-30cm (or any increase) with a particular global mean surface temperature change at a particular time in the future is difficult and highly problematic due to the long-term character of sea level rise and its response to global warming. Regional sea level changes are also likely to be different from the global mean changes. More fundamentally sea level rise due to the thermal expansion of the ocean arising from increased heat input due to elevated levels of greenhouse gases and the response of ice sheets occurs over a long time period. Indeed centuries are required for the ocean to come into full equilibrium with change levels of radiative forcing. As a consequence the sea level rise expressed at any point in time is a fraction of that which is likely to occur for the full response to elevated greenhouse gas concentrations. One way to characterize the response is estimate the warming, which if held constant, would result in a commitment to a certain sea level rise. This is also fraught with difficulties not the least of which is the very broad range of uncertainty in sea level rise estimates. From this point of view warming to date, if

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Coastal wetlands	Europe	Loss of coastal wetlands in Atlantic Baltic and Mediterranean coasts for the 2080s. Atlantic coast 0 to 17%[42] Baltic coast 84 to 98% Mediterranean coast 31 to 100%	2.6-4.4°C[43]	Projections for coastal wetland losses for the 2080s in the European region indicate that the Baltic and Mediterranean coasts are most vulnerable. These estimates are based on new runs of the model described by (Nicholls *et al.* 1999), whose global results are shown below. See IPCC WGII TAR Table 13-4 for the full results. These were constructed using the four preliminary IPCC SRES marker scenarios and roughly span a temperature increase relative to 1990 of 2.0-3.8°C with a central estimate of sea level rise of 36-42cm[44]. The range of losses shown opposite is the result of sea level rise uncertainty, which is larger than the range mentioned in the preceding sentence, and uncertainty in relation to the response of wetlands. Nevertheless the WGII TAR Chapter 13 notes that under the high scenario wetlands in the Baltic and Mediterranean would be eliminated which "could have serious consequences for biodiversity in Europe, particularly for wintering shorebird and marine fish populations" (Kundzewicz *et al*. 2001).	Model based assessment of the vulnerability of each region to sea level rise taking into account local factors.
Coastal Wetlands	USA	Extensive loss of wetlands in southern New England	3-5°C[45]	Recent rates of sea level rise of about 2mm/yr along with local subsidence rates of about 1mm/yr have led to the displacement of high marsh species with less rich cordgrass (Donnelly and Bertness 2001a). It is expected that if current rates of sea level rise continue then high coastal marshes will be further displaced by cordgrass in the coming century. Higher rates of sea level rise than around 2mm/yr, as projected for next century, will cause the cordgrass to drown and there will be extensive overall loss of wetlands in southern New England. Local accretion rates are in the range of 2-6mm/yr. Sea level rise of around or greater than 6 mm/yr could be anticipated to result in large wetland losses. Warming in the range of 3-5°C in 2100 (above 1861-1890) could be expected to produce local sea level rise rates above 6mm/yr. It should be noted that associating a specific temperature increase with a rate of sea level rise is difficult and uncertain, nevertheless a warming rate as above would most likely lead to a rate of sea level sea level rise sufficient to overwhelm the adaptive capacity of the marshes.	Sea level rise in excess of accretion rates will results in the loss of wetlands. High marshes when invaded frequently with saltwater are replaced by cordgrass. If the rate of sea level rise exceeds the accretion rates possible regionally then total loss of wetland occurs.
Coastal Wetlands	USA	Wetland losses in Delaware. 21%	>2.5-3.5°C[46]	Sea level rise projected for 2100 would reduce Delaware's land area by 1.6% and likely cause loss of around 21% of the wetlands in the area (Najjar *et al.* 2000).[47] This loss of wetland area occurs for a local sea level rise of about 70cm of which	Rate of sea level rise exceed capacity of marshes and wetlands to adapt given estimates of potential accretion

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maintained could already mean a commitment to a sea level rise of 30cm or more. At the other extreme one can simply associate the range of sea level rise estimates with the time a which they occur under a range of scenarios. In this case an estimate of global mean warming at the time of the sea level rise of interest can be made, although it suffers from the inadequacy described above. The IPCC TAR estimates that sea level rise over the coming century would be in the range of 0.8 cm-8 cm/decade. A 10-30 cm global sea level rise would correspond to a warming in the range of 1-3°C. The range of GCM models available with temperature and sea level rise projections available on the IPCC Data Distribution Centre website indicate that at the time of a 10 cm sea level rise global mean warming is likely to be in the range 0.9-1.3°C. For a 30cm sea level rise the range would be 2-2.8°C (above 1961-1990). The 1961-1990 mean is around 0.3°C above 1861-1890.

[42] The higher losses are associated with the higher temperatures and sea level rise. See the general discussion in footnote 41.

[43] This the approximate range of global mean temperature increases associated with the losses of coastal wetlands in the European assessment. The temperature increases are for the year 2100 (not the 2080s) and are with respect to 1861-1890. See footnote 44 for the source.

[44] See Table 3-9 of IPCC WGII TAR Chapter 3 (Carter *et al.* 2001) for a summary of these scenarios, but noting that the SRES A1 scenario was split into three markers in the final SRES scenario set up. This resulted in the upper end of the A1 range having a higher warming than the A2 scenario but this was not included in the scenarios for European sea level rise and coastal wetland loss.

45 See level rise rates above 2mm/yr may well result from temperature increases less than this.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
				This loss of wetland area occurs for a local sea level rise of about 70cm of which about 20cm is due to local effects.[48] As consequence of the projected sea level increase, current 100-year floods are projected to occur 3-4 times more frequently. Under current rates of sea level rise (around 2mm/yr), high coastal marsh species are being displaced by low-marsh species like cordgrass. Over the last century, cordgrass has been able to keep pace with or surpass rates of SLR of 2 to 6 mm/year, however local sea level rise of around 6 mm/yr or greater is possible for the warming range projected for 2100. Rates of change of this magnitude could lead to the drowning of cordgrass communities and extensive loss of coastal wetlands in southern New England. Given the inertia of sea level rise, the warming that actually causes this sea level rise would be less and correspondingly, a warming at this level would result in much greater sea level rise in the 22nd and following centuries.	given estimates of potential accretion rates and other factors. As much of the area affected is undeveloped inland migration of some of the wetlands may be possible.
Coastal Wetlands	USA	Significant loss of important foraging, migratory and wintering bird habitat at five sites in the USA. 20-70%[49]	2.6°C [50]	The effects of two temperature and sea level rise scenarios (2°C and 4.7oC temperature increase above 1990 with a corresponding increase in sea level rise of 34 cm and 77cm by 2100) on migratory shore bird habitat is estimated by (Galbraith *et al*. 2002). The results are complex in that whilst all sites loss substantially in all scenarios by 2050 and all but one site lose substantially by 2100 for the 2oC scenario, two sites (Bolivar flats and Delaware) gain significantly by 2100 in the high scenario. Major losses are projected at four sites - Willapa Bay, Humboldt Bay, San Francisco Bay, and Delaware Bay by 2100 for the 2oC scenario, which could threaten their ability to support current populations of shorebirds. The worst losses are where existing sea walls constrain inland migration of the habitats. The 34cm case is for a global temperature increase of 2oC (above 1990) and is assessed as having a 50% probability (Titus and Narayanan 1996). The 77cm sea level rise is associated with a temperature increase of 4.7oC and assessed as having a 5% probability (Titus and Narayanan 1996).	Most severe losses occur where coastal topography is steep or where infrastructure prevents inland migration of wetlands. The assessment model accounts for ability of local sedimentation rates to preserve intertidal flats in the context of sea level rise. Local topographic features including current human infrastructure are included. In the Bolivar flats case it is assumed that all areas above the current extreme high water mark would be protected by new infrastructure.
Coral Reefs	Global	Annual or almost annual bleaching by 2040 with negative implications for coral reefs and for coral reef biodiversity, and for communities dependent on reef	1.7-2.3°C[51]	Bleaching frequency increases with temperature and the crossing of local bleaching thresholds. Hoegh-Guldberg (1999) investigated the relationship between seasonal sea surface temperature anomalies and coral reef bleaching events historically. He found a strong relationship between periods of high temperature and bleaching events. The temperature thresholds in several reef locations for bleaching varied by species and location. Using scenarios driven by IS92a or similar from the ECHAM4 and CSIRO-MkII models and downscaled to each location he found that the frequency of bleaching is likely to	An apparent threshold of seasonal temperature increases is found to exist that varies by reef location. When crossed coral reefs bleach and may take many years to recover. The temperature threshold for the same species varies across its geographic range, indicating that acclimation has

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46 This is the global mean increase in temperature that corresponds to rates of sea level at or above 6mm/yr.

[47] Under the scenarios used by Najjar *et al*. (2000) the sea level rise used here corresponds in time to a global mean temperature increase of around 3.5°C above 1861-1890. Using the HadCM2 model driven by the IPCC IS92a emissions including sulphur aerosols. The other model used in the Najjar *et al*. (2000) work, the Canadian Climate Centre (CCC) model, has a warming of about 4°C for the same period (2095).

48 The sea level rise projections, using the IS92a scenario, are drawn from the IPCC SAR WGI Chapter on changes in sea level rise, with a local component of 2mm/yr. See Table 1 of Najjar *et al*. (2000) for details of the scenarios used.

[49] Range of losses for the 2oC scenario for all sites except Bolivar flats which gains by 1.8%.

[50] This is the temperature at the time of the sea level rise assumed in this study. See footnote 41.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
		based resources.		increase in the future for most reefs. For both models by the 2040s bleaching is projected to occur (or nearly) annually for all of the reef sites. No account is taken of changes in El Niño frequency or intensity.	occurred over the long term.
Coral Reefs	Indian Ocean	Risk of local extinction of coral reef by 2010-2025 for many coral reefs in the Indian Ocean between 10-15°S	0.9-1.4°C[52]	Sheppard (2003) estimated bleaching rates based on observed bleaching patterns from record 1998 bleaching events. Bleaching threshold varies by reef location for the same species across its range. Local extinction risk is diagnosed when coral bleaching is estimated to occur every five years. Reefs north and south of the 10-15°S band have later "extinction dates". Sheppard notes "the fact that most sites between 0^o and 15^o south will have a 1 in 5 probability annually of suffering a month as warm as that of 1998 within 10–15 years means that several of the world's poorest countries, for which reefs provide essential resources will be affected soonest". The HadCM3 scenarios closely match for the 2020s the scenarios from the HadCM2 model (Hulme *et al*. 1999a).	The mechanism is very similar to that described in Hoegh-Guldberg (1999). Sheppard (2003) defines the extinction date of coral locally as the year in which the probability of bleaching approaches 20%. With bleaching at frequencies of more than five yearly, recovery appears unlikely. The lethal level of temperature during the warmest month is defined with respect to those temperatures observed to be lethal during the 1998 bleaching events. Small increase in acclimation of the corals would significantly extent the period before extinction occurred (raising this to higher temperatures).
Freshwater systems	USA – Prairie Pot Hole Region	Major reduction in waterfowl breeding population and wetland extent. Breeding population		The Prairie Pothole Region is the most important breeding area for waterfowl in North America (Sorenson *et al.* 1998). The wetlands appear to be more sensitive to temperature increase than to precipitation changes. Both of the climate models used project a major increase in drought conditions. Under the Hadley model transient scenarios, the drought severity gradually increases from mild average drought in May in the 2020s, to moderate average drought in the 2050s corresponding to global mean temperature increases of 2.2 and 3.3°C respectively.[53] Under this model bird breeding numbers are reduced from the average 5 million in the 1955-1996 period by 25% and around 45%. There is also projected to be loss of wetland quality, with less open water area preferred by ducks.	Wetlands are sensitive to an increase in temperature and summer drought. Large increases in precipitation would be necessary to offset the effects of increased temperature.
		25%	2.5°C		
		45%	3.6°C		
Freshwater systems	USA – Rocky Mountains	Large reductions in habitat for cold water Salmonid fish Rocky Mountains.		Habitat changes as a consequence of warming for Salmonid fishes were estimated for a range of local summer warmings for June, July and August (1-5°C) (Keleher and Rahel 1996). Suitable habitats were mapped as those with summer temperature (JJA) less than 22°C, which is known to be suitable for	Increases in stream water temperature estimated to reduce suitable range.

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[51] Temperature increase range of the models used for the decade of the 2040s above either 1861-1890 for the ECHAM4 models or 1890-1900 for the CSIRO model. Estimated from the data in the IPCC DDC archived date set for the CSIRO and ECHAM models forced by IS92a, with and without aerosols.

52 Range of warming from the HadCM3 model used by Sheppard (2003) for the period 2010-2025. See http://ipcc-ddc.cru.uea.ac.uk/cru_data/visualisation/visual_index.html for graphical comparison with other scenarios and also Table 1 of Hulme *et al*. (1999a).

[53] These temperatures, 2.2°C and 3.3°C are those cited by Sorenson *et al.* (1998) for the global mean temperature increase for the 2020s and 2050s from the UM Meteorological Office/Hadley model runs cited (Murphy 1995; Murphy and Mitchell 1995). It is assumed here that they are with respect to 1961-1990, although this is not stated in the paper, except in so far as the base period for bird estimates is 1955-1996. More recent HadCM2 and HadCM3 scenarios indicate lower warming levels for these years – 1.5°C and 2.4°C (wrt 1861-1890) respectively (Hulme *et al*. 1999a).

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
		17% 50% 72% Wyoming 14% 43%	0.8-1.0°C [54] 1.8-2.4°C 2.7-3.8°C 1.3-1.7°C 2.7-3.8°C	Salmonid fish species. The corresponding global mean temperature changes are in the range 0.8°C-3.8°C.[54] Salmonid range reductions for this span of temperature increases were in the range 17% to 72% for the Rocky Mountain habitats. For the Wyoming habitats the range reductions were smaller - 7 to 43%.	
Freshwater systems	USA-southern Appalachian Mountains	Substantial reduction in habitat, and a much smaller reduction in abundance, of trout species. Abundance 10% brook trout 24% rainbow trout Habitat 80%	1.1-2.3°C [55]	Individual model of fish life cycle coupled to GIS database of streams in southern Appalachian Mountains with scenarios for warming in summer produced complex pattern of changes. An overall decline in abundance of Brook trout (10%) and rainbow trout (24%) is projected (Clark *et al.* 2001). Lower elevations were projected to experience largest losses. The warming scenarios applied were for a 1.5-2.5°C increase in summer water temperature above 1977-1982, which corresponds to a global mean increase of around 1.1-2.3°C above 1861-1890.[55]	Warming of freshwater streams combined with changes in stream flow reduce suitable habitats, but abundance changes are linked to a complex set of negative and positive effects on the lifecycle of the fish. Warning water alone increases abundance.
Biodiversity Hotspot	South Africa – Succulent Karoo	Very large range reduction and possible complete loss of Succulent Karoo with likely extinction of many, if not most, of the 2500 plants endemic to the region. Range Reduction 80% 100%	1.9-2.4°C [56] 3.4-4.3°C [57]	The Succulent Karoo contains the richest arid flora on the planet and hosts around 2500 endemic plants. Climate change appears to a first order threat to these species. Two Climate Models, HadCM2 and CSM model downscaled to local grid and with bioclimatic model of species at high resolution (Midgley *et al*. 2003). (Hannah *et al.* 2002) estimate that the Succulent Karoo could lose more than 80% of its range by 2050 with the future bioclimatic region being far from its present range. A range loss of 80% is likely to lead to very large levels of extinction in the longer term. The IPCC TAR WGII reported that Rutherford *et al.* (1999a) estimated the complete loss of the Succulent Karoo for a warming of 3-4°C.[57] Complete loss of range would imply major biodiversity losses.	Projected increase aridification in this winter rainfall region will reduce the climatically suitable zone for many of the endemic species. Land use effects do not appear to be decisive. It seems unlikely that the species of this region would be able to migrate to the Agulhas plain. This much further to the south and east and would involve migration across the Cape Fold Mountains.[58]

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[54] As before the global mean changes were estimated using SCENGEN for nine recent models downscaled to a broad region covering the Rocky Mountains and Wyoming for the June/July/August period using the SRES A1B-AIM marker scenario. The model mean for this was 1.73°C JJA increase per degree global mean surface temperature increase, with an inter-model standard deviation of 0.31°C/°C. The latter was used to define the range for each estimate. Note that using other scenarios produces different scalings, which would increase the range shown here.

[55] Estimated using SCENGEN for nine recent models downscaled to a broad region covering the southern Appalachian Mountains for the June/July/August period using the SRES A1B-AIM marker scenario. The model mean for this was 1.67°C JJA increase per degree global mean surface temperature increase, with an inter-model standard deviation of 0.40°C/°C. The latter was used to define the range for each estimate. The offset from the 1977-1982 global mean to 1861-1890 was estimated to be 0.37°C using the Folland and Anderson (2002) data set. Note that using other scenarios may produce different scalings, which would increase the range shown here.

[56] As the projected range reduction is based on the HadCM2 scenario for the 2050s, this temperature range is estimated using the HadCM2 range for both sulphate and greenhouse gas only ensemble average in 2050s accessed from http://ipcc-ddc.cru.uea.ac.uk calculated from model generated increase in 2050s relative to 1961-1990 (1.6-2.1°C) plus the observed increase from 1860s (0.32°C). An alternative approach, which would yield a larger range is to assume that the range reduction would occur at around the same local temperature increase in any model and to take the range of models or the standard deviation of the inter model estimates for this ratio.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Biodiversity Hotspot	South Africa – Fynbos or Cape Floristic Province	Very large range reductions for the Fynbos biome, which would threaten many of its 5600 endemic species. Range Reduction 51-61%	1.9-2.4°C [56]	The Fynbos is a unique and extremely rich region and forms the smallest of the six flora kingdoms. It is projected to lose 51-61% of its area for a warming in the range 1.9-2.4°C. As a consequence about one third of the species suffer "complete range dislocation" by the 2050s (Midgley *et al*. 2002).[59] In other words unless the species can migrate they will become extinct. Around 10% of the 330 endemic *Proteaceae* species are projected to suffer complete range loss. A high-resolution bioclimatic modeling approach was used driven with three GCM scenarios (HadCM2) with and without aerosols, and the CSM scenario without sulphur. HadCM2 produced the lowest global temperature increase (Midgley *et al*. 2002). Range dislocation is used as indicator of extinction risk (Midgley *et al*. 2003).	Warming moves the suitable bioclimatic region south and east and upwards. The effects are expected to be mitigated by the topographic complexity of the mountains in the region which provide more opportunity for suitable habitat to remain. For many of the most at risk *Proteaceae* species land use change has less effect than climate change due to the projected altitudinal shift of species (Midgley *et al*. 2003). In the higher regions over 50% are in reserves (Rouget *et al*. 2003).
Mammals and birds	Mexico	Large range losses for species projected. 90% or more loss 0-45 species 50% or more loss 93-355 species	1.9-2.4°C [56]	Large numbers of species appear to be at risk in Mexico. Using an ecological niche model with three classes of species dispersal abilities the effects of climate change in Mexico on all of its 1,870 mammal, butterfly and bird species was estimated for the 2050s (Peterson *et al*. 2002). The climate scenarios used were based on the HadCM2 model with two different emissions and corresponded to global mean warming in the range 1.7-2.4°C (above 1861-1890). With range loss being a powerful predictor of species extinction, these results are quite	The most serious effects were projected for the flatlands in the north of Mexico and the Chihuahuan desert. This was caused by more drastic range reductions than in the mountainous regions (Peterson 2003).

There are different ways to do this. If it is assumed that the range reduction (80% or more) occurs at local temperature increase associated with the HadCM2 range and one takes the standard deviation of the model range used here, then the minimum global mean temperature at which this would occur is around

[57] Baseline is 1961-1990 (Midgley 2003), e.g. 3.3-4.6°C above 1861-1890 average.

[58] Rutherford *et al.* (1999a) and see http://www.nbi.ac.za/climrep/5.htm.

[59] See also http://www.nbi.ac.za/climrep/6.htm.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
				concerning for the future of a large number of species in Mexico.	
Mangroves	Bangladesh	Losses of forests and wetlands in Sundarbans. Area lost 15% - 10 cm SLR 40% -25cm SLR 75% -45cm SLR 100% -60-100cm SLR	1-1.5°C[60] 1.5-2.5°C 2.0-3.5°C 3.0-4°C	The IPCC identified the mangrove forests and wetlands of the Sundarbans as a unique entity threatened by climate change and sea level rise. Known as the largest intact mangrove wetland system in the world it is the sole remaining home of the Royal Bengal tiger (*Panthera tigris tigris*).[61] A diverse plant flora grows in the region and the forest is known to support 425 species of wildlife – 49 mammal species, 315 bird species, 53 reptiles and 8 amphibians. Sea level rise is predicted to result in the progressive loss of the mangrove forest and wetlands, including habitat of Bengal tiger (Qureshi and Hobbie 1994; Smith *et al*. 1998). Estimates of loss for a given level of sea level rise are drawn from the following sources. An estimate of impacts for a 45cm sea level rise was made in Chapter 2 of an Asia Development Bank report (Qureshi and Hobbie 1994). Smith *et al.* (1998) estimated the loss for 1 metre of sea level rise, which provided the basis for the estimates made in the IPCC TAR WGII Chapters 11 and 19 (Lal *et al.* 2001; Smith *et al.* 2001). Other values are interpolated using the results from these reports (See also World Bank (2000)).	Freshwater systems and forests would become inundated, impairing the growth and reproduction of species that rely on fresh water. With the productivity of the system declining, the closed canopy forests would be replaced by shrubs and bushes, leading to loss of species.
Mediterranean systems	Europe	Increased drought risk is likely to cause major vegetation changes.	1.3-3.8°C[62]	Recent droughts and associated tree mortality in Spain have indicated that some tree species that are important to Mediterranean ecology are at present close to the edge their ability to cope with drought stress (Martinez-Vilalta and Pinol 2002; Ogaya *et al*. 2003). Projections of the effects of future climate change indicate a substantially increased risk of tree mortality for some evergreen species such as the Holm oak (*Quercus ilex*) due to increased temperature and extended droughts (Martinez-Vilalta *et al*. 2002). Holm oak is an important species to the Mediterranean landscape. Forest currently dominated by it could be invaded by other species (*Pinus latifolia*) that are more resistant to drought and temperature changes. A strong threshold effects is observed in the modelling, which is supported by observed effects during the severe 1994 drought in the region. If the drought periods extend beyond 3 months there is a sudden increase in tree mortality.[63]	Tree mortality exhibits a strong dependence in the length of the dry period or drought rather than temperature. A strong threshold effect is observed not far above present day water stress levels.

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[60] As pointed out in footnote 41 these estimates are difficult. The range of temperatures here are those corresponding to the global mean surface temperature increase at the time at which the sea level rise is reached under a range of scenarios taking into account a range of models.

[61] It spans about 1 million km^2, 62% of which is in Bangladesh and the remainder in West Bengal, India.

[62] Local summer (June/July/August) temperature increase of 1.5, 3 and 4.5°C relative to 1999-2000 converted to global mean increase using SCENGEN. The scaling factors used were 1.855°C/°C with an inter-model standard deviation of 0.424°C/°C.

[63] The model used treats drying as synonymous with death, however Holm oak is capable of resprouting. However the authors note that *Holm oak* seems to be very close to it's water stress limit under present climate conditions and that trees that are forced to resprout every few years will be at a competitive disadvantage in relation to undamaged trees. See Figure 2 of Martinez-Vilalta *et al.* (2002) for the threshold response-

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Mediterranean ecosystems	Europe	Increased fire frequency as a consequence of climate change projected to lead ecosystem shift to shrub dominated landscapes.	1.9-2.4°C[64]	Increased drought and water stress predicted for the north western Mediterranean region are likely to lead to large changes in fire frequency, which in turn is likely to lead to large changes in vegetation (Mouillot *et al.* 2002). Using a dynamic vegetation model SIERRA and climate scenario Mouillot *et al*. (2002) projected that there would be increased fire frequency with reduction in return period for forests from 72 to 62 years and for shrub lands from 20 to 16 years. The warming scenario was an annual increase locally of about 2.4°C relative to 1960-1997 (the summer period warmed by about 4.0-4.8°C) with precipitation decreases in the Mediterranean region (Gregory and Mitchell 1995). The increase fire frequency led to changes in vegetation structure in the model.	Increased frequency of drought projected under warming scenarios in the region leads to increase fire frequency and water stress. This leads to consequential changes in the vegetation, shifting it to shrublands from woodland/forest. Dense forest and grasslands in particular decline in favour of low shrub and high shrubs.[65]
Montane Cloud Forests	Hawaii	Predicted extinction of three species of Hawaiian Honeycreepers.	2.8-3.2°C[66]	Climate change is predicted to act synergistically with past land use changes and avian malaria risk, to substantially reduce or eliminate the viable habitat of several Hawaiian honeycreepers (*Drepanidae*) (Benning *et al.* 2002). The honeycreepers live in montane tropical forests, which has been confined to higher elevations as consequence of past agricultural land clearance. Above this forest the high elevation area are subject to use for pasture. An introduced mosquito whose upward range is limited by temperature honeycreeper at lower altitudes would be subject to attack and mortality from avian malaria. While past land use change has led to endangerment these pressures are not predicted to make the species extinct.	Warming of the atmosphere is predicted to lead to rising cloud base around the mountains. This would in principle displace montane forest upwards, however migration is limited by the upper elevation land use. Rising temperatures at the present elevation range of the honeycreeper would lead to an increase risk of contracting avian malaria.
Plant species	Europe	Severe risks projected for biodiversity. About one third or more of the species present in 1990 in nearly half (44%) of the European land area are projected to disappear from these areas by 2050 due to the movement of their bioclimatic zone.	2.4°C[67]	The bioclimatic zones occupied by species are projected to move with climate change. The IMAGE 2 climate model and the EUROMOVE bioclimatic envelope model have been used to estimate the changes in biome suitability for nearly 1400 plant species in Europe. The historical climate envelope for these species was determined for these species and then the effects of climate change on their distribution in 2050 projected (Bakkenes *et al*. 2002). Drier and more arid regions are found to be the most vulnerable to change – south western Europe, central European Russia and the Ukraine. Less than 50% of current species are projected to remain *in situ* in Spain, southwestern France, the Black Sea coast and Byelorussia. The lowlands of Germany, Belgium and The Netherlands are likely to keep 70-80% of their species, however some endangered species may disappear.	Warming and other climate changes will lead to the movement of suitable bioclimatic zones for many species. The EUROMOVE models establish the bioclimatic envelope for the species studied and then estimate how this will change after climate change. The actual migration of species in order to tracking the movement of their bioclimatic zones is uncertain for a number of reasons. It is by no means clear that all of the species whose bioclimatic zones move away from current locations will be able to re-establish successfully.

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[64] A 2.4°C local warming with respect to 1960-1997 is upscaled to a global mean estimate with SCENGEN using scaling factors of 1.373/°C with an inter-model standard deviation of 0.199°C/°C for the northwest Mediterranean region. The period 1960-1997 is about 0.38°C warmer than 1861-1890. Whilst the study uses the climate scenario of the UKTR model (and earlier Hadley transient scenario) upscaling the local warming (as this is given in the paper) to the global mean gives a better idea of the uncertainty range involved.

65 For the scenario (S2) involving changes in both rainfall and temperature. See Figure 6 of Mouillot *et al.* (2002).

[66] A 2°C local warming upscaled to a global mean estimate with SCENGEN using scaling factors of 0.851°C/°C with an inter-model standard deviation of 0.073°C/°C for the equatorial Pacific region assuming the local increase is with respect to 1990.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Protected areas	Africa	Major adverse consequences predicted for Malawi's Lengwe National Park (and for Malawi in general). It is unlikely that it would be able to support large populations of ungulates if climate change produces more drought conditions and consequent degradation of habitat.	2.9-3.4°C[68]	Projected climate changes in the Malawi region are estimated to have adverse effects on wildlife (Mkanda 1996, 1999). Recent drought periods were used as an analogue to future projected changes by comparing the droughts of 1979/80 and 1991/92 with several GCM projections. Mkanda (1996; 1999) found that there was little difference between the projected effects of the different GCM scenarios for a doubled CO_2 climate. The increased evapotranspiration caused by higher temperatures outweighed the benefits of increased precipitation in these scenarios. Consequently it is predicted that land and vegetation quality is likely to be much degraded by climate changes in the future, with the possibility of a "vicious cycle developing" with poor ground caused by climate change driving further soil degradation and reduced habitat quality.	Increase temperatures lead to more frequent drought conditions in this region. Increased precipitation projected in some scenarios does not appear sufficient to compensate for increased evapotranspiration.
Protected areas	North America	High altitude plant species in Yellowstone national park may not cope with climate change arising from a doubling of CO_2 concentration.	4-8°C[69]	Complex changes are projected for the vegetation of the Yellowstone national park as a consequence of projected climate change. The range of high elevation species is reduced and some species disappear from the region (Bartlein *et al*. 1997). Bartlein *et al*. (1997) argue that the rates of change projected may exceed the ability of species to migrate as rates of change exceed those evident from the paleorecord. An early generation GCM from the Canadian Climate Centre (CCC) was used for this scenario. A global mean warming of 3.5°C was estimated for doubling of CO2 concentrations (Boer *et al*. 1992). When downscaled to the Yellowstone region this produced a warming of about 10°C in January and July. Such warming for this level of global mean change in this area are not generally found in the most recent generations of coupled ocean atmosphere GCMs. As these seasonal warming levels were used to drive the assessment of vegetation effects, the global mean estimates here are upscaled using the recent generation of AOGCMs. It should also be noted that there is most of the current generation of models project a decrease in summer rainfall (model average -9%/°C global warming) in this region whereas the CCC model used had little change. Such a reduction would exacerbate many of the effects cited by Bartlein *et al*. (1997).	Warming and increased summer drought stress, with consequent increase in fire frequency, lead to substantial changes in vegetation. The later generation of climate models predict a reduction in summer rainfall on average, which would exacerbate the problems identified.

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[67] The scenario used was computed with the IMAGE 2.0 driven by the IPCC IS92a scenario, which generated a global increase of 1.8°C above 1990 by 2050. As before the 1990 climate is assumed to be about 0.6°C warmer than the 1861-1890 period.

[68] The global mean warming was calculated using SCENGEN. The local temperature increase scenarios used by Mkanda (1999) of 3.1-3.8°C to the global level upscaled using the scaling factors 1.123°C/°C with an inter-model standard deviation of 0.25°C. Whilst Mkanda used early generation GCM scenarios a check against the projections from the current generation of models indicates that these are not inconsistent. Combined with his findings that the scenarios he used produced relatively robust results (increased temperatures tended to outweigh the effects of increased rainfall projected from two of the three GCMs he used.

[69] This is the range of global mean temperature increases upscaled using SCENGEN from a warming of 10°C in January and in July in this region, as used in the Bartlein *et al*. (1997) analysis. The CCC model used as the basis for the scenario of Bartlein *et al*. (1997) has a global mean warming of 3.5°C, however more recent generation AOGCMs do not produce such pronounced warming in this region.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Protected areas	South Africa	Loss of two thirds of animal species studied in Kruger National Park.	1.9-3.1°C[70]	The bioclimatic range of many animals presently within Kruger National Park are projected to move outside of the park boundaries (Erasmus *et al*. 2002). Migration of these animals in order to track the range shift may be problematic due to land use pressures in the regions adjacent to the park (Erasmus *et al*. 2002).	In general there an eastward shift in ranges are projected with warming. Large movements of the bioclimatic zones of many animal species are projected to occur. Extensive range shifts are also projected for plant species in the region (Rutherford *et al.* 1999b). Substantial and growing land use and population pressures are very likely to cause major problems for migration of animals tracking climate induced movement of their ranges (Erasmus *et al.* 2002).
Protected areas	Switzerland	Many protected areas would no longer be suitable for a large numbers of their present forest species. <u>Proportion of reserves not suitable for present forest species</u> 40-50% 70-80%	 0.9-1.5°C[71] 1.4-2.8°C[72]	Based on lapse rate considerations, Kienast *et al.* (1998), assess the effects of increasing temperatures on mountain forest communities.[73] Twenty-nine out of 109 reserves have enough altitudinal range to survive a 500-metre change in effective climatic zone (a 2-2.8^{o}C increase) and 12 areas have enough range to survive a 250 metres change (1-1.4^{o}C increase). However 50 reserves (46%) cannot take a 250m gain and 18 areas have only enough altitude to survive a 250-metre range change. Calculations using degree-days yield similar results. Authors point to many limitations of the study including no dynamical assessment of changes, no account taken of land use changes etc.[74]	Climatic warming will lead to upward altitudinal movement of bioclimatic zones.

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[70] A 2-3°C temperature increase in South Africa with respect to 1960-1989 is converted to a global mean with respect to 1861-1890 using average of nine recent GCMs downscaled to the European Alpine region using SCENGEN. The regional to global scaling used is 1.191°C/°C with the range set by the inter-model standard deviation of 0.114°C/°C. The scaling factors using all 17 models in SCENGEN are not very different from the 9 model estimate. Within the paper the climate scenario is not detailed and references are made to it warming South Africa by 2°C and by 2.5-3°C. If 2°C then the global warming range is 1.9-2.2°C and 2.5-3°C then the range is 2.2-3.1°C. The full range is included here.

[71] A 1-1.4°C local temperature increase with respect to 1931-1970 converted to a global mean with respect to 1861-1890 using average of nine recent GCMs downscaled to the European Alpine region using SCENGEN. The regional to global scaling used is 1.39°C/°C with the range set by the inter-model standard deviation of 0.30°C/°C. The scaling factors using all 17 models in SCENGEN are not very different from the 9 model estimate. The base period is 1931-1970, which is about 0.26-0.28°C warmer than 1861-1890.

[72] A 2-2.8°C local increase above 1931-1970 converted to global mean as in footnote 71.

[73] Authors use an adiabatic lapse rate of 0.55°C/100m.

[74] The authors also used a spatially explicit forest simulator with four climate scenarios: moderate or strong temperature increases and current levels or a 15% increase in precipitation. The model area includes not only the reserves but also the entire Swiss forest inventory. For temperature increases only the model supports vegetation shifts along altitudinal lines, however with warmer and wetter conditions, model results indicate that vegetation shifts may not be as 'dramatic'. The model did not consider the effects of CO_2 fertilization. For strengths and weakness of bioclimatic envelope models see Footnote 3.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Species conservation	Australia	Large range reduction in range of butterfly species >20% range decline 54% of species >50% range decline 83% of species	1.2°C [75] 2.9°C [76]	Large range reductions are projected for many butterfly species in Australia as a consequence of projected climate change. Using the bioclimatic envelope model BIOCLIM the range changes for 24 species of butterflies were examined for a range of four climate change scenarios for the 2050s (Beaumont and Hughes 2002). The climate scenarios used were based on the results of seven climate models running under the IPCC SRES scenarios, with regional estimates over Australia (Hulme and Sheard 1999) – see footnotes 75 and 76. Changes in species distribution were estimated using the temperature and precipitation changes for grid cells over Australia. One of the main findings is that even species with wide climatic ranges could be very vulnerable to climate change. The proportion of species suffering large range contractions increases rapidly with temperature. The larger the warming the smaller is the proportion of a species current range that lies within the projected future range in the 2050s. For a small increase of global mean temperature of 1.2°C[75] this proportion is 66%, whereas for a larger global mean warming of 2.9°C[76], this falls to less than 22%.	Changes to temperature and precipitation result in geographic shifts in the suitable bioclimatic zones for butterfly species. The model projects the change in bioclimatic range from the 1961-1990 period to the 2050s. The ability of species to track these geographic changes is not modelled. It is known that many of the Australian butterfly species have limited dispersal ability or cannot migrate (Beaumont and Hughes 2002). Land clearance and habitat fragmentation appears likely to present barriers to dispersal and migration.
Species conservation	South Africa	Predicted local extinction of four animal species and large range reductions of greater than 50% for 29 endangered species. 140 species (78%) projected to experience various levels (4-98%) of range contraction.	1.9-3.1°C [70]	"Profound impacts" are projected for many animal species in South Africa from climate change (Erasmus *et al.* 2002). A bioclimatic envelope model approach was used to study the response of 179 animal species – 34 birds, 19 mammals, 50 reptiles, 19 butterfly and 57 other invertebrates in South Africa – under a scenario involving a 2-3°C increase above 1960-1989 mean temperature (as well as precipitation changes) (Erasmus *et al.* 2002). There were four projected local extinctions (see Table 2 of Erasmus *et al.* (2002)). The vast majority of species are projected to experience range reductions of the order of 4-98%. As a consequence of land use pressures and habitat fragmentation the ability of animals to track climate change by moving their range is open to doubt. Erasmus *et al.* (2002) point out that "theoretical range shifts into transformed landscapes may mean local extinction". The range reductions projected are conservative and appear likely to underestimate the overall reductions, as landscape transformation is not accounted for in the model.	Large range shifts are predicted as a consequence of climate change, mostly in an easterly direction across the region. Fragmentation of the landscape in the region as a consequence of human activities means the projected range shifts may not be realized in practice. Range reductions projected are likely to underestimate the actual overall loss of range for the same reasons. Reductions in range size are likely to increase the risk of local extinction.
Species conservation	Australia	Dramatic range reduction or disappearance of frogs, and endangered mammals and plants from Dryandra forest ecosystem in southwestern Australia.		"Dramatic decreases in range" (IPCC TAR WGII 12.4.2 (Pittock *et al.* 2001)) are projected for most species studied in the Dryandra forest ecosystem in southwestern Australia for quite small warming levels. Effects include the disappearance of frogs, and endangered mammals and plants (Pouliquen-Young and Newman 1999). A bioclimatic envelope model was used to estimate the effects of temperature and rainfall changes using a regional climate model at 125km resolution. The forested studied is part of a larger systems in south western Australia that has been identified as one of 25 global biodiversity hot spots (Myers *et al.* 2000). Three species of frogs, 15 species of endangered or threatened mammals, 92 varieties of the plant genus Dryandra, and 27 varieties	Bioclimatic envelope is estimated empirically and then climate change scenario superimposed.[78] Unsuitable soils and land use patterns several limit migration potential.

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[75] The scenario used is the B1-low of Hulme and Sheard (1999), which produces warming over Australia in the range 0.8-1.4°C warming wrt to 1961-1990. This scenario has a global mean warming for the 2050s of 0.9°C wrt 1961-1990 or 1.2°C wrt the 1861-1890 base period.

[76] The scenario used is the A2-high of Hulme and Sheard (1999), which produces warming over Australia in the range 2.1-3.9°C warming wrt to 1961-1990. This scenario has a global mean warming for the 2050s of 2.6°C wrt 1961-1990 or 2.9°C wrt the 1861-1890 base period.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
		All frogs and mammal species studied would be restricted to small areas or disappear Two thirds of Drvandra tree species and all of the Acacia species projected to disappear from the region.	1.1°C[77] 2.6°C	of Acacia were modelled. For 0.5°C warming above 1990 all frogs and mammal species studied would be restricted to small areas or disappear. Under warming of 2°C two thirds of Dryandra tree species and all of the Acacia species modelled would disappear from the region.	
Temperate forests and woodlands	Australia	Australian eucalypt species outside current thermal range. 25% 40% >50%	1.1-1.3°C[79] 1.9-2.2°C[80] 2.7-3.2°C[81]	Under the assumed warming scenarios the present bioclimatic zones of eucalypt species move significantly. As a result "within the next few decades many eucalypt species will have their entire present day populations exposed to temperatures and rainfalls under which no individuals currently exist" (Hughes *et al.* 1996). Using a bioclimatic model (Hughes *et al.* 1996) find that of the 819 species of Eucalyptus examined for their climatic range (mean annual temperature and rainfall), 53% have ranges spanning less than 3°C , 41% having a range of less than 2°C , and 25% have a range of less than 1°C . In relation to rainfall, 23% have ranges spanning less than 20% of the variation in mean annual rainfall. Although actual climatic tolerances of many species are wider than the climatic envelope they currently occupy, substantial changes in the tree flora of Australia may be expected (Hughes *et al.* 1996).	The present distribution of species is mapped against Empirical bioclimatic estimates of species range for temperature rainfall and other factors with superimposed temperature and rainfall scenarios.82 Migration of species is not modelled.
Temperate forests and woodlands	New Zealand	Risk of extinction of New Zealand kauri tree.	4.8-7.5°C[83]	Empirical, isolation and subsequent extinction feared (Mitchell and Williams 1996). A risk of extinction is identified in the TAR: "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."	Warming causes bioclimatic zone of kauri to move away from existing locations.

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[77] Adjusted to 1861-1890 from 0.5°C above 1990.

[78] For strengths and weakness of bioclimatic envelope models see Footnote 3.

[79] This the global mean temperature range corresponding to a warming over Australia of 1°C upscaled using SCENGEN. The scaling factors used of 1.161°C/°C (with a standard deviation of 0.121°C/°C) is the average of 9 recent AOGCMs computed choosing SCENGEN cells minimizing the area of oceans surrounding Australia as the impact being examined is for land surface. Although it is not clear what the base period is for the climate data an extensive data resource was used by the authors to map current eucalypt distributions against temperature and precipitation. In this context a conservative assumption is to use the 1961-1990 reference period.

[80] As for footnote 79 but for a 2°C local warming.

[81] As for footnote 79 but for a 3°C local warming

[82] For strengths and weakness of bioclimatic envelope models see Footnote 3.

[83] Assuming the 4°C local increase is with respect to 1990 and using SCENGEN as described above to obtain a local to global scaling for the South Island of New Zealand of 0.769°C/°C and an inter-model standard deviation of 0.193°C/°C.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
Tropical Forests	Australia	Loss of 50% of the highland rainforest habitat in the World Heritage listed tropical rain forests in North Queensland. These highlands host most of the more than 60 endemic vertebrates of this region.	1.6-1.8°C[84]	The tropical rainforests of North Queensland, Australia supports 566 species to terrestrial vertebrates or 28% of the Australian total. Sixty-five are regional endemics, most of which are hosted by the highland tropical forests within the region. Using a neural network bioclimatic model to project the effects of changes in precipitation and climate it has been found that large reductions in highland rainforest is likely in the wet tropics of North Queensland, Australia (Hilbert *et al*. 2001). Lowland mesophyll vine forest is projected to increase in areas but upland complex notophyll vine forest response depends on precipitation. Highland rainforest (simple notophyll and simple mesophyll vine fern forests and thickets) decreases for all rainfall scenarios for a 1°C increase in temperature. This habitat hosts many of the endemic vertebrates of the region and severe, adverse consequences have been predicted for many of these (see below).	Warming causes rise in bioclimatic zone. No assessment is made of effects of elevated CO_2.
Tropical Forests	Australia	"Predicted extinction" of Golden Bower bird and other species similarly confined to upland and highland areas of the wet tropical forests of North Queensland. <u>Range loss</u> >60% 90% 98%	1.6-1.8°C[84] 2.6-3.0°C[85] 3.6-4.2°C[86]	Climate change is predicted to lead to the extinction of the Golden Bower bird which is confined to upland and highland areas (Hilbert *et al*. 2003). Range losses for this species are projected to be approximately 90% with a 2°C warming and a 10% decrease in rainfall. This scenario is consistent with recent model estimates of climate change for the region (Walsh and Ryan 2000). Whilst the overall change in rainfall is uncertain, it is likely that there will be an increase in dry season severity and variability in rainfall (Walsh and Ryan 2000). .	The bioclimatic zone of the Golden Bower bird is extirpated with increasing temperature.
Tropical Forests	Australia	"Catastrophic" loss of endemic rainforest vertebrates projected.	>2.6-3.0°C[85]	Severe loss of rainforest vertebrate species is projected in the highland tropical forests of the region as consequence of warming. Williams *et al*. (2003) examined a wide range of species and found a risk of catastrophic loss of the endemic vertebrates of the forest above 300 metres: "Extinction rates caused by the complete loss of core environments are likely to be severe, nonlinear, with losses increasing rapidly beyond an increase of 2 °C, and compounded by other climate-related impacts". Most of the rainforest in the region is confined to above 300 metres altitude. Mountains in the region are no higher than about 1600 metres. Of the 600 vertebrate species in the region 83 are endemic, 72 of these are restricted to the rainforest and 62 of these confined to the montane forests above 600 metres	Verterbrates confined to high altitude zones are projected to run out of suitable habitat with increasing temperature. Williams *et al*. (2003) argue that the results for the wet tropics of Australia have broad implications for montane and higland tropical forests. These often are very diverse with large numbers of endemic species and may be "severely threatened by climate

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[84] Assuming the 1°C local increase is with respect to 1990 and using SCENGEN as described above to obtain a local to global scaling for the Wet Tropics area of 0.917°C/°C and with an inter-model standard deviation of 0.072°C/°C.

[85] Assuming the 2°C local increase is with respect to 1990 and applying the same scaling factors as in footnote 84.

[86] Assuming the 3°C local increase is with respect to 1990 and applying the same scaling factors as in footnote 84.

Ecosystem	Region	Impact	Global mean surface temperature above pre-industrial [°C][6]	Comments	Causal Chain
				altitude.	change” (Williams *et al.* 2003).
Tropical Forests	Amazon	Risk of collapse of tropical forests in the Amazon.	1.4-2.4°C[87]	Several studies have identified a risk of a climate change induced collapse of the Amazon rainforests. A firm probability statement cannot yet be made as to the likelihood of this coming about, however the seriousness of the risk and is large consequences mean that this needs to be taken seriously.[88] Based in part on a climate scenario driven by the HadCM3L model Cowling *et al.* (2003) argue that the feedbacks that maintained the stability of the Amazon in the past glacial and interglacial climates[i] cannot be maintained in the future and that there is likely to be a positive feedback effect which amplifies local drying and warming. As a consequence, Cowling *et al.* (2003) argue that there is a threshold “at which tropical ecosystems exceed their capacity for internal/external feedback effects compensating of the deleterious effects of warming on tropical plants,” but that locating this is very difficult. They speculate that the climate system, temperature, is very close to this threshold at present. Jones *et al.* (2003) report on the estimated carbon cycle feedback effects of climatic warming, updating the earlier work of Cox *et al.* (2000). An abrupt increase in the land source of CO2 as a consequence of warming and the pattern of climate change in the scenario occurs, reaching 7GtC/yr in 2001, principally from loss of soil carbon and Amazon tropical forest dieback. Apart from the drastic biodiversity loss implications such a feedback would amplify the warming considerably. See Note 1 at the end of this table for a further brief discussion on the Amazon and climate change issue.	One of the critical mechanisms is the effect of vegetation feedbacks on regional climate. Anthropogenic climate change leads to higher temperatures and increased respiration, which leads to a breakdown of water recycling within the Amazon basin. As rainfall declines this contributes to further vegetation dieback. In addition to the mechanism identified by Cowling *et al.* (in press), it seems likely that the habitat fragmentation-climate-forest fire feedback identified by Laurance and Williamson (2001) will act to exacerbate any purely climate change induced propensity of vegetation loss.
Tropical Forests	Amazon	Projected “dramatic” loss of species viability in eastern Amazonia with refugial areas remaining in the western zone of the Amazon basin	1.5-2.8°C[89]	The Amazon basin and its rainforests host a substantial fraction of the world’s biodiversity. Climate change is projected to lead to loss of species in parts of the Amazon (Miles 2002; Miles *et al.* 2003). Under a “standard” scenario[90] with warming by the 2080s of 2.5°C wrt 1990 29% of species are projected to have “no viable distribution”. Under a “reduced impact scenario”, with warming of 1.2°C by this time, 13% had no viable distribution projected. Dispersal or migration in many of these cases would have to occur over hundreds of kilometres for species to reach appropriate new bioclimatic zones.	The effects of climate change were estimated using bioclimatic modelling of plant species in the Amazon. This took account of tolerance of plants to extreme climate values, barriers to migration and dispersal, and lags in species response to climate change.

Note [1]: A major caveat on these results is that they are based on the HadCM3 climatic projections for the Amazon region and the TRIFFID vegetation/terrestrial carbon cycle model. The main driver of the collapse is the increasing El Nino like warming pattern for sea surface

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[87] This estimate of when an instability threshold may be approached in the Amazon is highly uncertain and most likely model dependent. The range chosen here is global mean warming for the HadCM3 model forced by the IS92a emissions scenarios for the period 2020s and 2050s (Hulme *et al.* 1999a). These time periods are chosen as the earliest period in which significant changes can be seen in Amazon rainforest cover and the time at which a reduction of around 20-25% has occurred in the modeling by Cox *et al.* (2003). See their Figure 6.

[88] Cox *et al.* (2003) conclude that whilst the mechanisms that could lead to a dieback of the Amazon are qualitatively understood “we are still a long way from being able to estimate the probability of such an ecological catastrophe occurring.”

[89] Scenarios used warm globally be between 1.2 and 2.5°C by 2095.

[90] Miles used the HadCM2 model for the assessment. It produces results within the range simulated by both the ECHAM4 and CSIRO MkII models for the Amazon region. The two main scenarios were a) Standard Impact based on the IPCC IS92a emission scenario. The standard scenario has a 2080s global mean temperature increase of ca 2.5°C w.r.t 1961-1990 and b) a Reduced Impact scenario of half this increase. Both are downscaled to the region.

temperatures projected by the HadCM3 model as greenhouse gases increase (Cox *et al.* 2003). Whilst some models show this as well it is not a universal feature. Nevertheless, the HadCM3 model has one of the best associations between current observed and modelled patterns of climate in this region. It was shown by Cramer *et al*. (2001) in a comparison of six dynamic vegetation models, and more recently in a review of the carbon cycle implications of projected climate (Cramer *et al.* 2003), that the vegetation feedbacks are model dependent. In particular the climate model and TRIFFID produce larger climate changes and larger, and qualitatively different vegetation responses than other models.

In spite of these uncertainties are several reasons for inclusion of this example. The main mechanism as described in the last column is likely to be driven, in addition to climate change, by land clearance in the Amazon. There is now a well established link between forest fires, habitat fragmentation and climate changes and extreme ENSO events in the Amazon (Laurance and Williamson 2001; Laurance *et al.* 2001; Nepstad *et al.* 2001; Cochrane and Laurance 2002). In other words there is likely to be a synergistic effect between forest fragmentation and deforestation and human induced climate change, should the latter lead to more ENSO like climatic conditions in the region. None of the models so far include these combined effects. Inclusion of such effects and processes would likely reduce the resilience of vegetation to warming and drying. Secondly, it seems likely that future climate change will produce more El Niño like conditions. It is known that there are substantial releases of carbon from the Amazon during ENSO years (Tian *et al.* 1998), which also occurs for the global biota (Jones *et al.* 2001). It is clear from the work of Tian *et al.* (1998) that the Amazon forest can switch from a sink to a source quite. Thirdly, smoke from biomass burning can inhibit rainfall over the Amazon (Rosenfeld 1999) implying a further and so far unmodelled feedback which would excarbate any tendency to drying and increase fire frequency. Fourthly, it is sometimes argued that the Amazon forest was substantially reduced in area during the last glacial and expanded with more equable climates in the early Holocene and hence a global warming reduced reduction would not be much different from what may have happened in the past. Based on a detailed analysis of available paleorecords Colinvaux *et al.* (2000) conclude that the Amazon forests retained their integrity throughout the last glacial period. This is supported by the modelling of Cowling *et al.* (2001; Cowling *et al.* 2003) with the indication that there feedback effects that help the forest cope with cooler and warmer periods. However recent work Cowling *et al.* (2003) indicates that these feedback processes could be overwhelmed by the climate changes projected by the models used. Finally, as a risk assessment exercise, the results of Cox *et al.* (2000), Cowling *et al.* (2003) and Cox *et al.* (2003), present a prima facie risk, that has yet to be eliminated by definitive modelling or other assessments.

3. Impacts on Food Production, Water, and Socio-economic systems

Introduction

Article 2 is quite specific in relation to the general need to “ensure that food production is not threatened”. However, it does not make mention of whether this should be the case regionally as well as globally. As will be seen from the information presented below this would have a substantial bearing on an interpretation of Article 2. Whilst current assessments indicate that global aggregate agricultural production may not be adversely affected up 2-3°C warming, this is not the case for a number of regions. Indeed, the questions of who will be adversely affected by climate change and who will make the “cruel choices”[91] between the costs of mitigation and the damages to be borne by climate change are amongst the key political issues involved in the resolution of the questions embodied in Article 2 and its implementation.

The other part of Article 2, dealt with here, relates to the need for policy action to be taken “within a timeframe sufficient to enable economic development to proceed in a sustainable manner”. Differing interpretations of this requirement have been made, with a dominant ‘economic’ one relating to the concept that if abatement action is to be rapid then economic growth would be reduced and resources diverted from other sustainable development needs. Another interpretation is that rapid climate change itself may threaten sustainable development in some regions and some sectors. The focus here is on information relevant to the latter question.

In general, the results presented below account for adaptation possibilities in each of the sectors considered. Only in cases where there are identified limitations to adaptation or where adaptation options have not been included, specific reference will be made to this issue.

With the emphasis in this report on brevity and on salience to a consideration of impacts at different temperature levels, the information below will be drawn largely from only a few studies of global impacts and effects based on a few GCMs. Whilst every attempt will be made to place these in the context of general findings or qualifications made in the IPCC TAR, the reader should be aware that the overall literature is rich, complex and sometimes divergent. In general, all of the literature chosen for use here is consistent with the broad findings of the TAR and where it is not, the reasons for this are specifically addressed. Space limitations militate against explanation of processes leading to impacts and effects and hence the discussion will focus on results only except to the extent necessary for clarity of exposition. The reader is referred to the underlying literature for an understanding of the processes mentioned below.

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[91] Phrase used by a key negotiator from a very large industrial country to describe the process of deciding upon the ultimate limits to climate change and the trade-off between the economic and political costs of emission abatement and climate protection targets.

Context: Findings of the Second and Third Assessment Reports

Projected climate change effects on the sectors considered here were examined in detail in the Second Assessment Report (SAR) of the IPCC (1995) and in the IPCC Regional Impacts report of 1997. The IPCC TAR in many cases explicitly reviewed the findings of these reports in its assessment of the literature. With few exceptions, the TAR confirms the general findings of the earlier assessments, however quantitative assessments have often changed.[92] Table 6 cross compares broad areas of the findings from the Second and Third Assessment Reports.[93] It gives a clear picture of the consistency between the findings of the 1995 and 2001 assessments. Consistency of these assessments, based as they are on quite different literature and different models at different stages of development, appears to add confidence to the overall findings of the IPCC TAR.

One of the main conclusions of the IPCC TAR, which strengthens the earlier SAR assessment, is in relation to the vulnerability of developing countries at low levels of warming (less than 2^{o}C). It is likely that global increases in temperature would produce net economic losses in many developing countries for all magnitudes of warming and these losses would be greater the higher the warming. This conclusion is reflected in each of the sectors discussed below, where many developing countries are seen to have large projected damages at low levels of warming, even though global aggregate market impacts are estimated as small or positive, up to a few ^{o}C warming. This is particularly true for agriculture and water resources where it is clear that some regions are particularly vulnerable to the effects of climate change.

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[92] It is important to bear in mind that more recent impact assessments have used transient scenarios generated with coupled Atmosphere Ocean General Circulation Models (AOGCMs) rather than, as was the case in the SAR, doubled CO_2 equilibrium scenarios run with Atmosphere General Circulation Models (AGCMs) with stylised (slab or mixed layer oceans). In general, the transient scenarios produce less extreme results at specific time periods in the future than the equilibrium scenarios.

[93] Space does not permit doing this for the Regional Impacts report, which contains much additional information, however the most salient findings of this report are repeated, in one form or another, in the IPCC Working Group II TAR Report.

Table 6 - Comparison of Second and Third Assessment Report Findings

Category	IPCC Second Assessment Report[94]	IPCC Third Assessment Report[95]
Vulnerability	“People who live on arid or semi-arid lands, in low-lying coastal areas, in water-limited or flood-prone areas, or on small islands are particularly vulnerable to climate change” (p. 29).	"The effects of climate change are expected to be greatest in developing countries in terms of loss of life and relative effects on investment and the economy. For example, the relative percentage damages to GDP from climate extremes have been substantially greater in developing countries than in developed countries” (WGII-SPM p. 8). “The projected distribution of economic impacts is such that it would increase the disparity in well-being between developed countries and developing countries, with disparity growing for higher projected temperature increases (*medium confidence*)” (WGII-SPM p. 8). Africa: “Increases in droughts, floods, and other extreme events would add to stresses on water resources, food security, human health, and infrastructures, and would constrain development in Africa (*high confidence*).” “Significant extinctions of plant and animal species are projected and would impact rural livelihoods, tourism, and genetic resources (*medium confidence*)” (WGII-SPM p. 14). Asia: “Extreme events have increased in temperate and tropical Asia, including floods, droughts, forest fires, and tropical cyclones (*high confidence*).” “Sea level rise and an increase in intensity of tropical cyclones would displace tens of millions of people in low-lying coastal areas of temperate and tropical Asia; increased intensity of rainfall would increase flood risks in temperate and tropical Asia (*high confidence*)” (WGII-SPM p. 14). Latin America: “Loss and retreat of glaciers would adversely impact runoff and water supply in areas where glacier melt is an important water source (*high confidence*).” “Floods and droughts would become more frequent with floods increasing sediment loads and degrade water supply in some areas (*high confidence*).” “Increases in intensity of tropical cyclones would alter the risks to life, property, and ecosystems from heavy rain, flooding, storm surges, and wind damages” (WGII-SPM p. 15).

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[94] Conclusions cited are from the Summary for Policy Makers of Working Group II of the Second Assessment Report adopted in Montreal, October 1995 unless otherwise stated. Where reference is made to WGII Technical Summary or to sections of the report it should be noted that these have not been approved in detail by governments.

[95] Conclusions are from Summary for Policy Makers of the Working Group II Report (WGII-SPM) and the Synthesis Report (SR-SPM) of the Third Assessment Report adopted at Geneva in February 2001 unless otherwise stated. Where reference is made to the full Synthesis Report or other sections of the IPCC TAR it should be noted that these have not been approved in detail by governments. The confidence levels are those assigned by IPCC WGII under its scale of uncertainties. See footnote 99 d.

		Small Islands: “Populations that inhabit small islands and/or low-lying coastal areas are at particular risk of severe social and economic effects from sea-level rise and storm surges. Many human settlements will face increased risk of coastal flooding and erosion, and tens of millions of people living in deltas, in low-lying coastal areas, and on small islands will face risk of displacement. Resources critical to island and coastal populations such as beaches, freshwater, fisheries, coral reefs and atolls, and wildlife habitat would also be at risk” (SR–SPM p. 12).
Health	“Climate change is likely to have wide ranging and mostly adverse effect on human health, with significant loss of life” (p. 35). “Indirect effects of climate change include increases in the potential transmission of vector-borne infectious diseases (e.g., malaria, dengue, yellow fever, and some viral encephalitis) resulting from extensions of the geographical range and season for vector organisms” (pp. 34-35). “Projections ... indicate that the geographical zone of potential malaria transmission in response to world temperature increases at the upper part of the IPCC-projected range (3-5^{o}C by 2100) would increase from approximately 45% of the world population to approximately 60% by the latter half of the next century. This could lead to potential increases in malaria incidence (on the order of 50-80 million additional annual cases, relative to an assumed global background total of 500 million cases), primarily in tropical, subtropical, and less well-protected temperate-zone populations” (p. 36).	“Overall, climate change is projected to increase threats to human health, particularly in lower income populations, predominantly within tropical/subtropical countries” (SR–SPM p. 12). “Climate change can affect human health directly (e.g., reduced cold stress in temperate countries but increased heat stress, loss of life in floods and storms) and indirectly through changes in the ranges of disease vectors (e.g., mosquitoes), water-borne pathogens, water quality, air quality, and food availability and quality (*medium to high confidence*)” (SR–SPM p. 12). “Climate-related health effects are observed. Many vector-, food-, and water-borne infectious diseases are known to be sensitive to changes in climatic conditions. Extensive experience makes clear that any increase in floods will increase the risk of drowning, diarrheal and respiratory diseases, water-contamination diseases, and—in developing countries—hunger and malnutrition (*high confidence*)” (Synthesis Report p. 56). “Heat waves in Europe and North America are associated with a significant increase in urban mortality, but warmer wintertime temperatures also result in reduced wintertime mortality. In some cases health effects are clearly related to recent climate changes, such as in Sweden where tick-borne encephalitis incidence increased after milder winters and moved northward following the increased frequency of milder winters over the years 1980 to 1994” (Synthesis Report p. 56-57). Latin America: “The geographical distribution of vector-borne infectious diseases would expand poleward and to higher elevations, and exposures to diseases such as malaria, dengue fever, and cholera will increase (*medium confidence*)” (WGII-SPM p. 15). Africa: “Extension of ranges of infectious disease vectors would adversely affect human health in Africa (*medium confidence*)” (WGII-SPM p. 14).

		Asia: "Human health would be threatened by possible increased exposure to vector- borne infectious diseases and heat stress in parts of Asia (*medium confidence*)" (WGII p. 14). Small Islands: "Many tropical islands are now experiencing high incidences of vector- and water-borne diseases that are attributed to changes in temperature and rainfall regimes, which may be linked to events such as ENSO, droughts, and floods. In the Pacific, there is growing evidence that outbreaks of dengue are becoming more frequent and appear to be strongly correlated with the ENSO phenomenon" (IPCC WGII Chapter 17 p. 864). "Climate change will cause some deterioration in air quality in many large urban areas, assuming that current emission levels continue (medium to high confidence)" (IPCC WGII Chapter 9 p. 453) "In areas with limited or deteriorating public health infrastructure, and where temperatures now or in the future are permissive of disease transmission, an increase in temperatures (along with adequate rainfall) will cause certain vector-borne diseases (including malaria, dengue, and leishmaniasis) to extend to higher altitudes (medium to high confidence) and higher latitudes (medium to low confidence)" (IPCC WGII Chapter 9 p. 453). "In some settings, the impacts of climate change may cause social disruption, economic decline, and displacement of populations. The ability of affected communities to adapt to such disruptive events will depend on the social, political, and economic situation of the country and its population. The health impacts associated with such social-economic dislocation and population displacement are substantial [high confidence; well-established]" (IPCC WGII Chapter 9 p. 454).
Agriculture	"Recent studies support evidence in the 1990 assessment that, on the whole, global agricultural production could be maintained relative to baseline production in the face of climate change modeled by GCMs at doubled-equivalent CO_2 equilibrium conditions. However, more important than global food production—in terms of the potential for hunger, malnutrition, and famine—is the access to and availability of food for specific local and regional populations" (WGII Technical Summary).	Europe: "There will be some broadly positive effects on agriculture in northern Europe (*medium confidence*); productivity will decrease in southern and eastern Europe (*medium confidence*)" (Synthesis Report p. 128). North America: "Some crops would benefit from modest warming accompanied by increasing CO_2, but effect would vary among crops and regions (*high confidence*), including declines due to drought in some areas of Canada's Prairies and the U.S. Great Plains, potential increased food production in areas of Canada north of current production areas, and increased warm temperate mixed forest production (*medium confidence*). However, benefits for crops would decline at an increasing rate and possibly become a net loss with further warming (*medium confidence*)" (Synthesis Report p. 128).

	"At broader regional scales, subtropical and tropical areas—home to many of the world's poorest people—show negative consequences more often than temperate areas. People dependent on isolated agricultural systems in semi-arid and arid regions face the greatest risk of increased hunger due to climate change. Many of these at-risk populations live in sub-Saharan Africa; South, East, and Southeast Asia; and tropical areas of Latin America, as well as some Pacific island nations" (WGII Technical Summary). "... many of the world's poorest people - particularly those living in the subtropical and tropical areas and dependent on isolated agricultural systems in semi-arid and arid regions are most at risk of increased hunger" (p. 33) "Increases in atmospheric carbon dioxide concentrations may raise the carbon-nitrogen ratio of forage, thus reducing its food value" (p. 30).	Latin America: "Yields of important crops are projected to decrease in many locations even when the effects of CO_2 are taken into account; subsistence farming in some regions could be threatened (*high confidence*)" (Synthesis Report p. 128). Asia: "Decreases in agricultural productivity and aquaculture due to thermal and water stress, sea-level rise, floods and droughts, and tropical cyclones would diminish food security in many countries of arid, tropical, and temperate Asia; agriculture would expand and increase in productivity in northern areas (*medium confidence*)" (Synthesis Report p. 128). Africa: "Grain yields are projected to decrease for many scenarios, diminishing food security, particularly in small food-importing countries (*medium-high confidence*)" (WGII-SPM p. 14). Small Island States: "Limited arable land and soil salinization makes agriculture of small island states, both for domestic food production and cash crop exports, highly vulnerable to climate change (*high confidence*)" (WGII-SPM p. 17). Australia and New Zealand: "The net impact on some temperate crops of climate and CO_2 changes may initially be beneficial, but this balance is expected to become negative for some areas and crops with further climate change (*medium confidence*)" (WGII-SPM p. 15). "Climate change represents an additional pressure on the world's food supply system and is expected to increase yields at higher latitudes and lead to decreases at lower latitudes. These regional differences in climate impacts on agricultural yield are likely to grow stronger over time, with net beneficial effects on yields and production in the developed world and net negative effects in the developing world. This would increase the number of undernourished people in the developing world (medium confidence)." (IPCC WGII Chapter 9 p. 454). "Agricultural yields will increase for most crops as a result of increasing atmospheric CO_2 concentration. This effect would be counteracted by the risk of water shortage in southern and eastern Europe and by shortening of growth duration in many grain crops as a result of increasing temperature. Northern Europe is likely to experience overall positive effects, whereas some agricultural production systems in southern Europe may be threatened [medium confidence, established but incomplete evidence]" (IPCC WGII Chapter 13 p. 643).
Human infrastructure	"Climate change and resulting sea level rise can have a number of negative impacts on energy, industry and transportation infrastructure; human settlements; the property insurance industry; tourism; and cultural	Asia: "Sea level rise and an increase in intensity of tropical cyclones would displace tens of millions of people in low-lying coastal areas of temperate and tropical Asia; increased intensity of rainfall would increase flood risks in temperate and tropical Asia (*high confidence*)" (WGII-SPM p. 14).

	systems and values” (p. 34). “Protection of many low-lying island states (e.g., the Marshall Islands, the Maldives) and nations with large deltaic areas (e.g., Bangladesh, Nigeria, Egypt, China) is likely to be very costly (High Confidence).” (Executive Summary of Chapter 9). “Adaptation to sea-level rise and climate change will involve important tradeoffs, which could include environmental, economic, social, and cultural values (High Confidence)” (Executive Summary of Chapter 9). “In some societies, resettlement, for example, would lead to dislocation of social and cultural groups and might even involve the loss of cultural norms and values...” (Chapter 9.6.3.3).	*confidence*)” (WGII-SPM p. 14). Small Islands: “The projected sea level rise of 5mm yr^{-1} for the next 100 years would cause enhanced coastal erosion, loss of land and property, dislocation of people, increased risk from storm surges, reduced resilience of coastal ecosystems, saltwater intrusion into freshwater resources, and high resource costs to respond to and adapt to these changes (*high confidence*)” (WGII-SPM p. 17). Europe: “In coastal areas, the risk of flooding, erosion, and wetland loss will increase substantially—with implications for human settlement, industry, tourism, agriculture, and coastal natural habitats. Southern Europe appears to be more vulnerable to these changes, although the North Sea coast already has high exposure to flooding [high confidence]” (IPCC WGII Chapter 13 p. 644).
Water resources	“Relatively small changes in temperature and precipitation, together with the non-linear effects on evapotranspiration and soil moisture, can result in relatively large changes in runoff, especially in arid and semi-arid lands. High-latitude regions may experience increased runoff due to increased precipitation, whereas runoff may decrease at lower latitudes due to the combined effects of increased evapotranspiration and decreased precipitation. Even in areas where models project a precipitation increase, higher evaporation rates may lead to reduced runoff” (WGII Technical Summary). “Climate change ... can have major impacts on regional water resources” (p. 32). “The quantity and quality of water supplies already are serious problems today in many regions...making countries in these regions particularly vulnerable to any	“Climate change will exacerbate water shortages in many water-scarce areas of the world. Demand for water is generally increasing due to population growth and economic development, but is falling in some countries because of increased efficiency of use. Climate change is projected to substantially reduce available water (as reflected by projected runoff) in many of the water-scarce areas of the world, but to increase it in some other areas (*medium confidence*) …. Freshwater quality generally would be degraded by higher water temperatures (*high confidence*), but this may be offset in some regions by increased flows” (SR-SPM p. 12). “Projected climate change would exacerbate water shortage and quality problems in many water-scarce areas of the world, but alleviate it in some other areas. … Climate change is projected to reduce streamflow and groundwater recharge in many parts of the world but to increase it in some other areas (*medium confidence*)” (Synthesis Report p. 72). Africa: “Changes in rainfall and intensified land use would exacerbate the desertification processes. Desertification would be exacerbated by reduction in the average annual rainfall, runoff, and soil moisture in countries of west African Sahel, and northern and southern Africa (*medium confidence*). Increases in droughts and other extreme events would add to stresses on water resources, food security, and human health, and would constrain development in the

	additional reduction in indigenous water supplies" (p. 32). "Experts disagree over whether water supply systems will evolve substantially enough in the future to compensate for the anticipated negative impacts of climate change on water resources and for potential increases in demand" (p. 32). "… The impacts, however, will depend also on the actions of water users and managers… In some cases—particularly in wealthier countries with integrated water-management systems—these actions may protect water users from climate change at minimal cost. In many others however—particularly those regions that already are water-limited—substantial economic, social, and environmental costs could occur. Water resources in arid and semi-arid zones are particularly sensitive to climate variations because of low-volume total runoff and infiltration and because relatively small changes in temperature and precipitation can have large effects on runoff" (WGII Technical Summary).	region (*high confidence*)" (Synthesis Report p. 130). Asia: "Water shortage— already a limiting factor for ecosystems, food and fiber production, human settlements, and human health— may be exacerbated by climate change. Runoff and water availability may decrease in arid and semi-arid Asia but increase in northern Asia (*medium confidence*)" (Synthesis Report p. 130). Europe: "Summer runoff, water availability, and soil moisture are likely to decrease in southern Europe, and would widen the gap between the north and south (*high confidence*). Flood hazards will increase across much of Europe (*medium to high confidence*); risk would be substantial for coastal areas where flooding will increase erosion and result in loss of wetlands" (Synthesis Report p. 130). Australia and New Zealand: "Water is likely to be a key issue (*high confidence*) due to projected drying trends over much of the region and change to a more El Niño-like average state" (Synthesis Report p. 130). North America: "Snowmelt-dominated watersheds in western North America will experience earlier spring peak flows (*high confidence*) and reduction in summer flow (*medium confidence*); adaptive responses may offset some, but not all, of the impacts on water resources and aquatic ecosystems (*medium confidence*)" (Synthesis Report p. 130). Small Islands: "Islands with very limited water supplies are highly vulnerable to the impacts of climate change on the water balance (*high confidence*)" (Synthesis Report p. 130).

Food Production and Agriculture

Apart from the uncertainty of future climate changes, the impacts of climate change on food production and agriculture depend on a range of factors. These include the vulnerability of agricultural activities, regions and populations to changes in climate and the capacity of these systems to adapt to the changes. Where vulnerability is high and adaptive capacity low there is likely to be the highest sensitivity to climate effects.

Relevant factors in determining the response of agricultural systems to climate change include:

- Rate and magnitude of changes in temperature and extremes of temperature. In the mid-latitudes increases in temperature, particularly increases in minimum temperature, can raise crop production providing water availability is not compromised. In the tropics crops are often close to thermal optimums, thus reductions rather than increases in production may result from increased temperatures.
- Changes in precipitation amounts and seasonality, drought, ENSO and other extreme event frequency, intensity and duration. If increased temperatures are accompanied by sufficiently increased precipitation, given that rising temperatures lead to elevated evaporation rates, crop yields may increase. Otherwise crop production may fall. Changes in extreme events are likely to influence crop production quite substantially (Mearns *et al.* 1997; Phillips *et al.* 1998; Rosenzweig *et al.* 2001) either directly or through changes in pest abundance and prevalence. Few attempts have been made to model extreme event effects on agricultural production.
- Effects of CO_2 fertilization on crop and grass production and yield. Increased CO_2 may increase water use efficiency of crops but is also likely to reduce the nutrient quality of the crops.
- Socio-economic conditions of rural populations and their access to markets, technology and resources needed for adaptation or for the acquisition of replacement food resources. Typically, in poor regions it is expected that farmers and those directly dependent on rural land activities will be most vulnerable to climate change.

Taken from the IPCC TAR Synthesis Report (TAR SYR), Table 7 summaries the findings of the IPCC TAR and attempts to place temperature-warming bands on impacts and effects. Other findings from the IPCC TAR, for which a temperature increase may be associated with changes in agricultural production, include:

- Agriculture in mid-latitude countries is expected with medium confidence to benefit for a warming of "a few degrees"[98] (2.6- 3.6^{o}C above 1861-1890[96]). Over 3-4^{o}C warming, there is low to medium confidence in a general decline in mid-latitude crop production along with quite pronounced drops in production elsewhere, leading to higher food prices (TAR SYR 4.2).

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[96] Unless otherwise noted temperature increases in this section will be cited with respect to the 1861-1890 average – see also Appendix I below.

Table 7 - Agricultural effects of climate change

Effect (change)	**2025**	**2050**	**2100**
CO_2 concentration[a]	405–460 ppm	445–640 ppm	540–970 ppm
Global mean temperature change from the year 1990[b]	0.4–1.1°C	0.8–2.6°C	1.4–5.8°C
Global mean temperature change from the years 1861-1890 (average)[97]	1.0-1.7°C	1.4-3.2°C	2.0-6.4°C
Global mean sea-level rise from the year 1990[b]	3–14 cm	5–32 cm	9–88 cm
Agricultural Effects[c]			
Average crop yields[g] [WGII TAR Sections 5.3.6, 10.2.2, 11.2.2, 12.5, 13.2.3, 14.2.2, & 15.2.3]	Cereal crop yields increase in many mid- and high-latitude regions (low to medium confidence[d]). Cereal crop yields decrease in most tropical and subtropical regions (low to medium confidence[d]).	Mixed effects on cereal yields in mid-latitude regions. More pronounced cereal yield decreases in tropical and subtropical regions (low to medium confidence[d]).	General reduction in cereal yields in most mid-latitude regions for warming of more than a few[98] °C (low to medium confidence[d]).
Extreme low and high temperatures [WGII TAR Section 5.3.3]	Reduced frost damage to some crops (high confidence[d]). Increased heat stress damage to some crops (high confidence[d]). Increased heat stress in livestock (high confidence[d]).	Effects of changes in extreme temperatures amplified (high confidence[d]).	Effects of changes in extreme temperatures amplified (high confidence[d]).
Incomes and prices [WGII TAR Sections 5.3.5-6]		Incomes of poor farmers in developing countries decrease (low to medium confidence[d]).	Food prices increase relative to projections that exclude climate change (low to medium confidence[d]).

No climate policy interventions. Source: Table 3-3 and references from IPCC TAR Synthesis Report with the addition of the row headed ‘Global mean temperature change from the years 1861-1890 (average)’. Summarized versions of the original notes a-d associated with these tables appear below.[99] Note g - these estimates are based on the sensitivity of the present agricultural practices to climate change, allowing (in most cases) for adaptations based on shifting use of only existing technologies.

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[97] Using Folland *et al*. (2001) global temperature data set.

[98] This term is not defined in Synthesis Report and nor is it defined in the Working Group II Report Summary for Policy Makers. Chapter 19 of the WGII TAR does define a range – see Appendix I of this report. In the Final Government Distribution of the Synthesis Report, which is the version upon which the final negotiated report is based and is prepared by the IPCC Lead Authors, “few” is defined as 2-3^{o}C above 1990. The removal of this specific definition was initiated and insisted upon by Saudi Arabia, amongst others, at the IPCC plenary where this report was adopted. Given this context “few” will be interpreted here in the original sense of the lead authors of the report. In terms of the 1861-1890 reference period, adopted in this report as surrogate for pre-industrial temperatures 2-3oC above 1990 corresponds to an increase of 2.6-3.6oC.

99 a. The ranges for CO_2 concentration are estimated for the six illustrative SRES scenarios, with the ranges for minimum and maximum values estimated for the 35 SRES projections of greenhouse gas emissions. See WGI TAR Section 3.7.3.

b. The reported ranges for global mean temperature change and global mean sea-level rise correspond to the minimum and maximum values estimated with a simple climate model for the 35 SRES projections of greenhouse gas and SO_2 emissions. See WGI TAR Sections 9.3.3 and 11.5.1.

- In the tropics and some subtropical regions (mostly developing countries), cereal crop yields are projected to drop with even minimal changes in temperature (TAR SYR Section 4.2).
- With low to medium confidence, it is expected that income of poor farmers will decline above a warming of 1.5-2°C.
- Above around a 2.5-3°C warming, it is estimated, with low confidence, that there will be a general increase in food prices. One study cited in the TAR (Parry *et al.* (1999) – see below) found prices to increase above around 1.6°C in the 2020s, however results in this temperature range are generally mixed.
- A review of the implications for rice production in Asia found that climate change is likely to seriously threaten sustained food production, with temperature increases above 2.6°C outweighing the positive effects of CO_2 increases (WGII Chapter 11.2.2.1 (Lal *et al.* 2001)).
- Australian crop yields were estimated to increase up to 1.6-2.6°C and then decline with higher temperatures, with it being noted that drops in rainfall caused rapid decreases in crop yield. It was reported that the most recent scenarios show reductions in rainfall over much of Australia. In the case of Australia, global mean warming in the range of 2.3-2.6°C,[100] has been projected to results in crop yields changing in the range of –3% to +3%, but significant areas in the west and the south would experience reductions. At higher temperatures, 4.2°C in the 2080s, entire areas are projected to be out of production, particularly in southwestern Australia (IPCC WGII TAR, Chapter 12 (Pittocket *et al.* 2001)).
- In general, for a global warming of about 2°C European crop production is expected to increase, with a few exceptions in the south of Portugal and Spain and in the Ukraine where decreases are estimated (IPCC WGII TAR, Chapter 13 (Kundzewicz *et al.* 2001)).
- In the USA, it was estimated that agricultural welfare would increase up to about 2°C and then decline at an increasing rate with the magnitude and direction of changes in rainfall being a decisive factor (IPCC WGII TAR, Chapter 15.2.3.1. (Cohen *et al.* 2001)).
- Large drops in the yield of maize and sugarcane are projected for small island countries for doubled CO_2 conditions (IPCC WGII TAR, Chapter 17.2.8 (Nurse *et al.* 2001)).

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c. Summary statements about effects of climate change in the years 2025, 2050, and 2100 are inferred from IPCC Working Group II's assessment of studies that investigate the impacts of scenarios other than the SRES projections, as studies that use the SRES projections have not been published yet. Estimates of the impacts of climate change vary by region and are highly sensitive to estimates of regional and seasonal patterns of temperature and precipitation changes, changes in the frequencies or intensities of climate extremes and rates of change. Estimates of impacts are also highly sensitive to assumptions about characteristics of future societies and the extent and effectiveness of future adaptations to climate change. As a consequence, summary statements about the impacts of climate change in the years 2025, 2050, and 2100 must necessarily be general and qualitative. The statements in the table are considered to be valid for a broad range of scenarios. Note, however, that few studies have investigated the effects of climate changes that would accompany global temperature increases near the upper end of the range reported for the year 2100.

d. Judgments of confidence use the following scale: very high (95% or greater), high (67–95%), medium (33–67%), low (5–33%), and very low (5% or less). See WGII TAR Box 1-1.

[100] SRES B2 and A1 scenarios; (Hulme and Sheard 1999).

More qualitatively a number of general conclusions were reached:

- Climate change is likely to exacerbate degradation of land and water resources.
- Elevated CO_2 combined with higher temperatures is likely to significantly reduce the protein and nutrient content of important cereal crops and of forage.
- Increased pest outbreaks with significant negative impacts on crop production seem likely for many crops and regions. Very few studies have included changed pest activity under climate change.
- Africa appears to be particularly at risk of increased hunger due to poverty and intrinsic vulnerability to climate change.

To look at this picture more closely attention will be focused on the findings of two recent global assessments. The first, published in 1999 by Parry and co-workers, was assessed in the IPCC TAR and its results were also presented in a synthesis of a range of impacts by Parry *et al.* (2001). Using the methodology and models from this work Arnell *et al.* (2002) compared the effects of an unmitigated emission scenario (IS92a) and concentration stabilization at 550 and 750 ppmv CO_2 scenarios with the HadCM2 GCM on a number of sectors including agriculture. The second is the Global Agro-Ecological Assessment for Agriculture in the 21st Century (also known as the GAEZ study) authored by Fischer *et al.* (2002) under the auspices of IIASA and the FAO.[101] This used a methodology built from a detailed bottom up, national level review of agricultural systems and was driven by several GCMs, including ECHAM4 and HadCM2.

Climate change and food security assessments

Several quantitative estimates of likely global impacts of climate change on food supply and the risk of hunger have been made over the last decade (Parry and Carter 1989; Rosenzweig and Parry 1994). In the 1994, study three early GCMs – the GISS, GFDL and UKMO models – were driven by an equilibrium CO_2 scenario for an increase of CO_2 from 330 to 550 ppmv in 2060. As is usual in these studies continued increases in crop yield and increase arable land availability were assumed. The results were strongly dependent on whether or not a CO_2 fertilization effect on crop yield was included and on the assumed level of adaptation. Under the first level of adaptation only small changes to the existing system were assumed. In this case the number of additional people at risk of hunger increased by 10-60% (60-350 million extra people at risk). These estimates decreased significantly when the second level of adaptation was assumed, which represented in the words of the authors, "a fairly optimistic assessment of the world's response to the changed climatic conditions tested."

Parry *et al.* (1999) used two of the latest generation of AOGCMs from the Hadley Centre which were driven by the IPCC IS92a emissions scenario to produce time dependant projections of future climate (see Table 9 below for an outline of the basic features of these scenarios of relevance here). Two kinds of adaptation were

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[101] IIASA, International Institute for Applied Systems Analysis; FAO, Food and Agriculture Organisation.

incorporated: farm level measures and economic adjustment effects. Geographically explicit crop models were used covering over 70% of the world's current wheat, maize and soybean production area, however less than half the rice growing regions were included. The crop models were driven using the effects of increased CO_2 and the projected climate changes from the model scenarios. Caution was expressed in relation to the assumed enhanced growth effects of CO_2 on crops included in the models, which the authors noted had not been verified in field conditions. Consequently, there is a risk that the positive yield effects assumed were overestimated (an issue also noted by Darwin and Kennedy (2000)).

Future increases in arable land were based on FAO data and did not account for the effects of climate change, an issue discussed in detail by Ramankutty *et al.* (2002)). The latter study finds that projected climate change is likely to increase the area of arable land suitable for crop production overall, with increases principally located in the Northern Hemisphere. However, the tropics (mainly Africa, northern South America, Mexico and Central America and Oceania) are likely to experience small reductions in suitable area. This general finding is confirmed in the IIASA study. Ramankutty *et al.* (2002) also point out that much of the land, that is at present or may become climatically suitable for agriculture in the future, is also under valuable forest cover.

Figure 9 shows a comparison of the results of these scenarios for two different time periods, the 2050s and 2080s (see explanation beneath figure), when temperatures are expected to have exceeded 2°C by a significant margin. The HadCM3 model produces more extreme results than the HadCM2 model, notably for large parts of the Northern Hemisphere. Whereas crop yields increase in these regions by the 2050s under some of the ensemble members[102] of the HadCM2 scenarios, under the HadCM3 scenario, which is drier and warmer than the HadCM2 scenarios, large areas in North America, Russia and eastern Europe experience reductions. By and large, crop yields are down in developing countries, under both models, with HadCM3 showing the most severe changes. In the 2050s, HadCM2 indicates that India is the worst affected of the developing countries with reductions of the order of 5-10%, whereas HadCM3 implies smaller damages in the range 0-2.5%. HadCM3 indicates that western Africa will experience the worst changes in the 2050s. By the 2080s, HadCM3 indicates larger damages in India (2.5-5% losses) and large losses in southern Africa. Figure 8 graphically demonstrates the range of effects projected by the different models and demonstrates that in general the regions at risk of production reductions are common to the two models, with the exception of North America. However, the quantitative scale of the reductions varies significantly.

In interpreting the results of this study it is important to bear in mind the uncertainties in this work. Apart from climate change itself, the question of whether and to what extent the CO_2 fertilization effect benefits production, the availability of irrigation water, trends in demand and the range of adaptation possibilities are all significant (Parry *et al.* 1999). Nevertheless, the overall changes and reductions in some regions translate to additional people at risk of hunger, with increasing temperatures tending to increase the number at risk (see Figure 10 below). Africa emerges from this study

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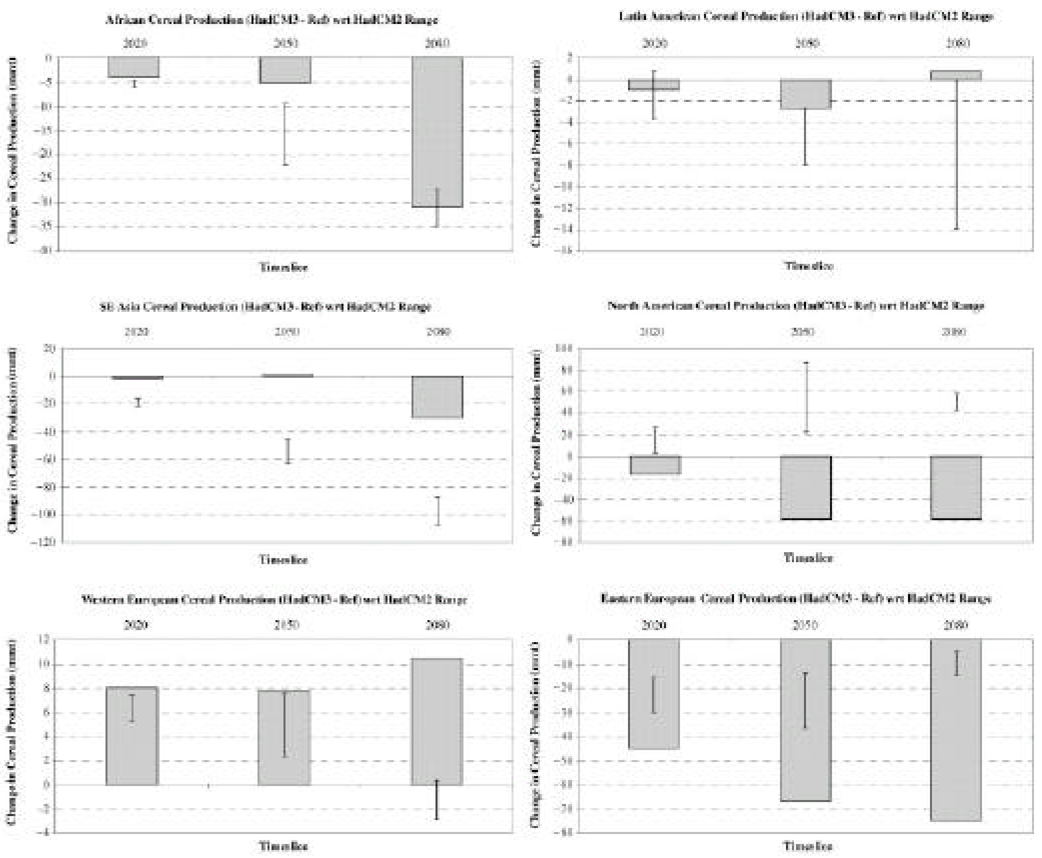
[102] Multiple runs of these complex models driven with the same emissions scenarios produce different results due to the 'natural' variability in the model climate system.

as a region particularly at risk from climate change under either of the models and has the largest share of the additional people at risk of hunger (see Table 8 below).

Figure 8 - Regional Impacts on Crop Production



Source: Figure 7 of Parry *et al*. (1999: S65). Shaded boxes are the HadCM3 results and the lines are the range of the HadCM2 ensemble results.

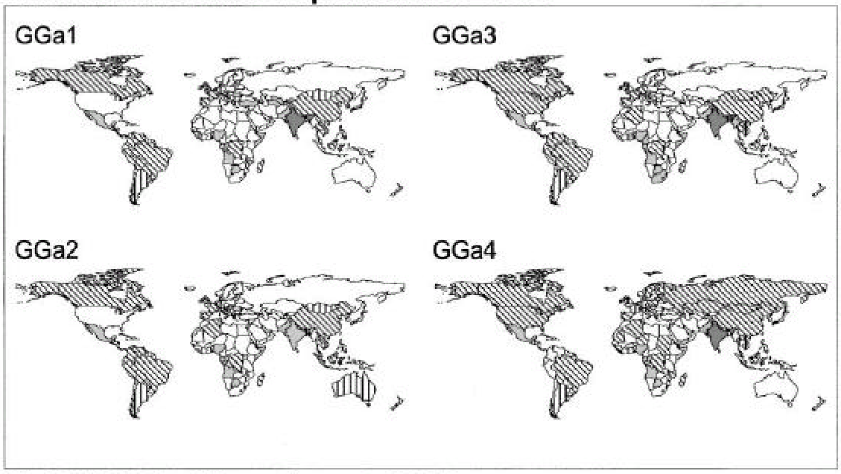
Table 8 - Risk of Hunger - Africa

Model	2080s temperature increase above 1861-1890 average	Impact
HadCM2	3.4°C	Africa: 55-65 million more people at risk of hunger. Globally: 80 million more at risk of hunger.
HadCM3	3.3°C	Africa: 70 million more people at risk of hunger. Globally: 125 million more at risk of hunger.

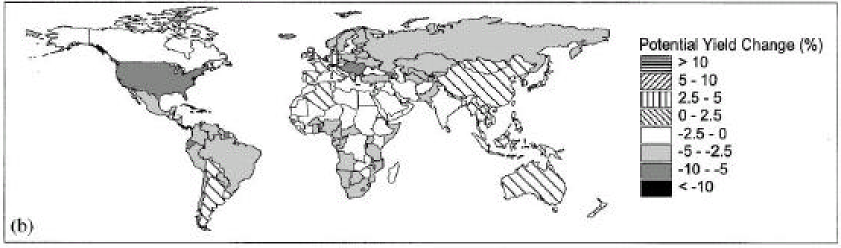
Note: Compiled from data in Parry *et al*. (1999).

Figure 9 - Comparison of Potential Crop Yields Projections for 2050s and 2080s

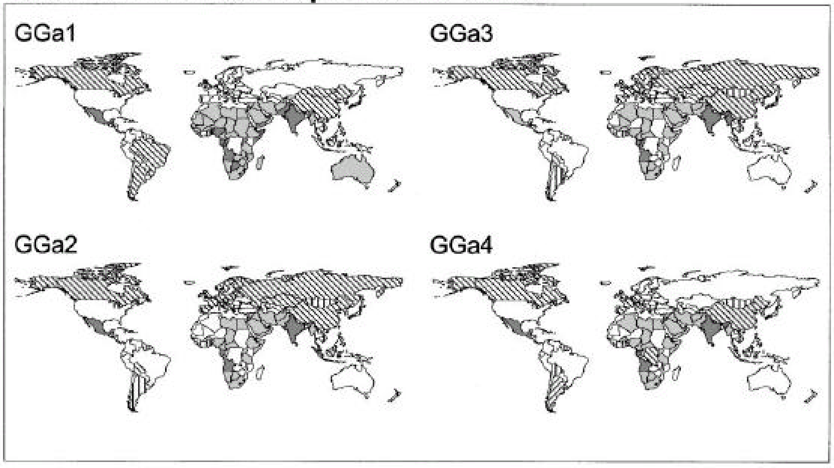
HadCM2 Ensemble Experiments- 2050s



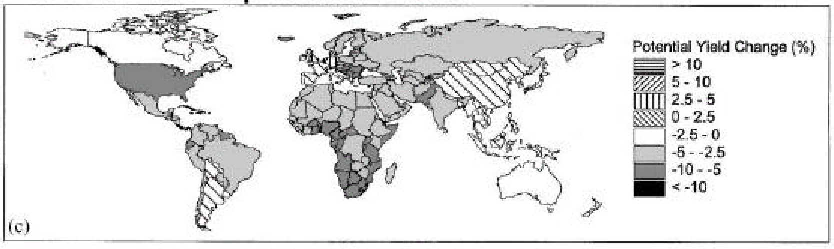
HadCM3GGa1 Experiment - 2050s



HadCM2 Ensemble Experiments- 2080s



HadCM3GGa1 Experiment - 2080s



Potential change in national cereal yields for the 2050s and 2080s, compared to 1990, for temperature increases of around 2.4°C and 3.3-3.4°C respectively compared to 1861-1890 for the HadCM2 and HadCM3 scenarios. The HadCM2 scenarios are for an ensemble of four members and the HadCM3 for a single scenario. Source: Figure 5 of Parry *et al.* (1999: S61).

Whilst the Parry *et al.* (1999) assessment provides insight into the risks faced from future climate change at different time periods into the future, it does not directly enable a comparison of risks at different levels of warming at different time periods in the future. Subsequent work by Parry *et al.* (2001) analysed projected effects at different temperature levels for the 2050s and 2080s. Known widely as the “Millions at Risk” paper, it provides a meta-analysis of several impact areas and enables some rough estimates to be made of impacts at different levels of warming at different times in the future. Perhaps most significantly, it also illustrates some of the dynamics of changing vulnerability over time and the interaction of this with projected climate changes. Levels of adaptive capacity are assumed to vary with time, with rising economic wealth being associated with higher levels of adaptive ability and greater resilience to climate change. One of the main drawbacks with this work, however, is that it is based essentially on one AOGCM, the HadCM2 model. Where possible, results from other models will be compared with the effects of the HadCM2 projections in order to at least provide a feel for the uncertainties involved.

For the food security issue, the data embodied in Figure 11 (based on the HadCM2 model climate projection) was used to estimate the levels of additional risk of hunger at warming of 1^{o}C, 2^{o}C, 2.5^{o}C and 3^{o}C, which are tabulated in the third column of Table 10.[103] For the 2050s, warming of 1-2.5^{o}C is estimated to produce an additional hunger risk of 4-7 million (this can be compared with the HadCM3 based estimate of close to 40 million people for around a 2.4^{o}C increase in 2050). Under the HadCM2 scenario, increasing temperatures in this time period are not projected to change the number at risk dramatically, as climate change is not projected to affect prices significantly in the 2050s. During this period, production in North America still increases (Parry *et al.* 1999). Over the following 30 years, there is an increase by a factor of 5-7 in the number at risk, as can be seen from the rapidly rising curve for hunger on the right hand side of Figure 11. At the maximum of the temperature scale for the 2080s, around 3.4-3.5^{o}C warming, the total number at risk of hunger are in the range 75-100 millions. The HadCM3 projections are higher for this period, on the order of 125 million (see Figure 10). This reflects an increasing sensitivity to climate change during this period and an increased population in vulnerable regions.

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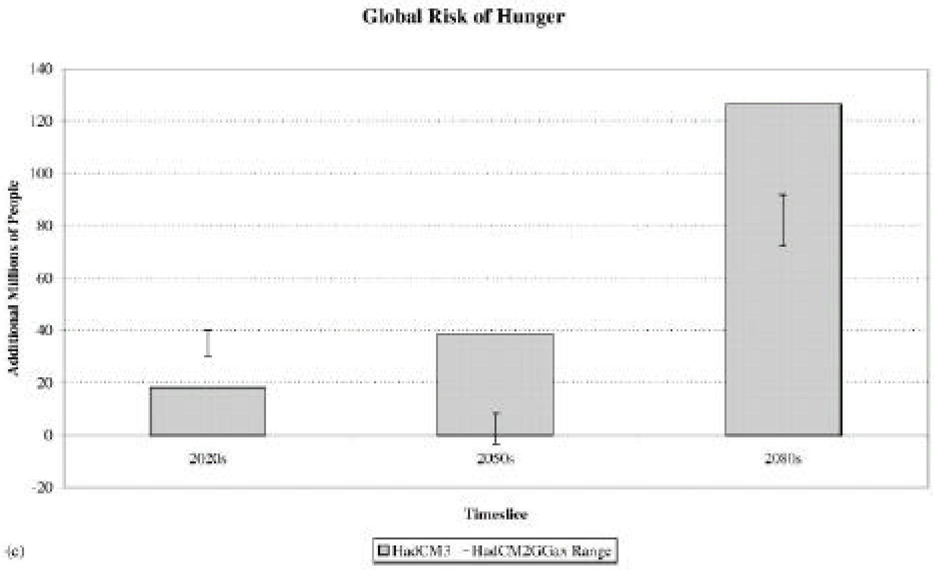
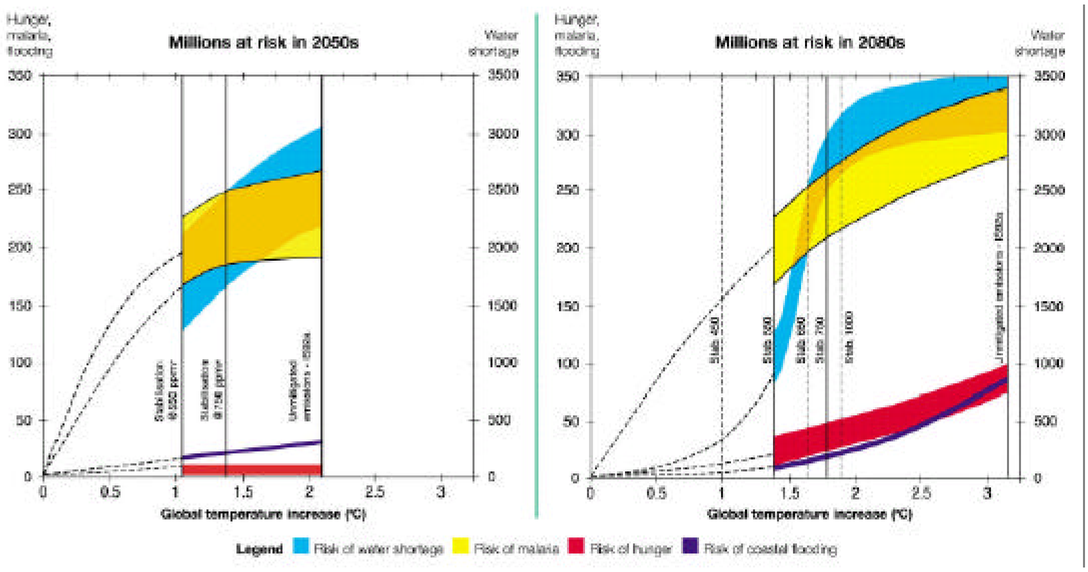
[103] For convenience, the results of the other impact areas assessed – health, flooding and water shortage are presented in the graph. However only the water shortage issue is discussed, as the other issues are beyond the scope of the present paper.

Figure 10 - Global Risk of Hunger



Source: Figure 6 (c) of Parry *et al*. (1999: S64). Shaded boxes are the HadCM3 results and the lines are the range of the HadCM2 ensemble results.

Figure 11 - Millions at Risk in 2050s and 2080s: Hunger, Malaria, Water Shortage and Flooding



This graph shows the estimated millions at risk associated with global mean warming levels above the 1961-1990 average based on the studies describe in Parry *et al*. (2001) which were driven by an ensemble of scenarios from the HadCM2 model. An error band of one standard deviation around the mean is shown, with the solid lines indicating model results and the dotted lines being inferred from these results. Source: This figure is a version of Figure 1 of Parry *et al*. (2001) taken from the web document "Defining critical climate change threats and targets: Discussion of the figures from Global Environment Change 11:3(2001):1-3" by the same authors, downloaded from www.jei.uea.ac.uk, February 2002, Jackson Environment Institute, School of Environmental Sciences University of East Anglia, Norwich NR4 7TJ United Kingdom.

Table 9 - Summary of Scenarios used in Global Food Security Assessment

Summary of scenarios	1961-90	2020s	2050s	2080s
HadCM2				
Temperature change (^oC)	0	1.2	2.1	3.1
Temperature change wrt 1861-1890	0.3	1.5	2.4	3.4
Precipitation change (%)	0	1.6	2.9	4.5
Sea-level rise (cm)	0	12	25	41
CO_2 (ppmv)	334	441	565	731
HadCM3				
Temperature change (^oC)	0	1.1	2.1	3.0
Temperature change wrt 1861-1890	0.3	1.4	2.4	3.3
Precipitation change (%)	0	1.3	2.4	3.2
Sea-level rise (cm)	0	12	24	40
CO_2 (ppmv	334	433	527	642

Source: Based on Table 1 of Hulme *et al.* (1999a) describing scenarios with the HadCM2 and HadCM3 model driven by the IS92a scenario with no aerosol forcing and used by Parry *et al.* (1999). The offset from 1961-1990 temperatures to 1861-1890 is with the Folland *et al.* (2001) global temperature data set.

Table 10 - Millions at Risk

2050s

Temperature in 2050s above 1861-1890 (above 1961-1990)	Malaria	Hunger	Water shortage	Coastal flooding
1^oC (0.7^oC)	163	4	1228	12
2^oC (1.7^oC)	224	7	2358	26
2.5^oC (2.2^oC)	227	7	2675	32

2080s

Temperature in 2080s above 1861-1890 (1961-1990)	Malaria	Hunger	Water shortage	Coastal flooding
1^oC (0.7^oC)	101	10	149	1
1.5^oC (1.2^oC)	165	21	562	8
2^oC (1.7^oC)	212	33	2427	19
2.5^oC (2.2^oC)	250	49	3117	36
3^oC (2.7^oC)	277	67	3245	57
3.4^oC (3.1^oC)	291	84	3473	79

Data estimated from figures in Parry, *et al.* (2001) using data-extractor software. Temperatures in parentheses are relative to 1990, the temperature base year used by Parry *et al.* (2001). These figures should be treated as indicative only, as they are based on visual interpolation using a graphical data digitising programme.

Global Agro-Ecological Assessment (GAEZ Study)

The IIASA/FAO assessment of agriculture over the next century (Fischer *et al.* 2001) produced qualitatively similar results to that of the Parry *et al.* (1999) assessment. Taking into account land suitability, population growth and other factors and a climate change scenario that brings around a 3°C warming in the 2080s, developing countries as a group suffer production losses. A large group of about 40 developing countries with a current population of 2 billion people, including around 450 million undernourished inhabitants, is projected to lose substantially, whilst about half the developing country group gain. Details of the projections for the group of developing countries experiencing malnourishment problems are found in Table 11. The 78 countries presently at some level of risk are divided into three groups.

Under the ECHAM4 climate scenario (see Table 12), a 3°C warming by the 2080s results in projected declines in cereal production, although at a world average level the volume of production is estimated to be sufficient to meet future needs. Developed countries as a whole are projected to experience a small loss in rain-fed cereal production. Within this picture 17 countries gain, though only two countries, Russia and Canada, enjoy 90% of the gain. The majority encompassing 60% of the population of the developed country group, including Belgium, the Czech Republic, France, Hungary, Romania, The Netherlands, United Kingdom, Ukraine, and the USA are projected to lose under this scenario (Fischer *et al.* 2001).

Table 11 - Malnourished Country Group and Climate Change

Group	Population	Proportion of population undernourished	Number of countries in group	Number of countries negatively affected	Impact
I 5-20% undernourished	2.1 billion	12%	28 Includes China	11	-10% decrease in cereal production. China gains
II 20-35% undernourished	1.5 billion	25%	27 Includes India with 60% of the undernourished	19 with over 80% of undernourished	Food deficit doubled
III More than 35% undernourished	440 million	50%	23 Most sub-Saharan African countries	10	Decrease in production 6 gain substantially

Compiled from Fischer *et al.* (2001: 27).

Within the developing country group, 65 countries are projected to experience production losses valued at US$56 billion in 1995 terms. These losses equate to 16% of the agricultural GDP of these countries (Fischer *et al.* 2001: 26). Africa appears to be the biggest loser in these scenarios, with 29 countries projected to suffer production losses. Kenya and South Africa are, however, projected to gain substantially from climate change. In Asia, China gains substantially whilst India loses (Fischer *et al.* 2001: 27). Overall Fischer *et al.* (2001) identify 40 "losing countries" with a total population close to 2 billion and an undernourished group of about 450 million. In these countries the gap between food production and supply is projected to double under climate change, “drastically” increasing the number suffering from under nourishment (Fischer *et al.* 2001: 28).

A cross comparison of the projected effects of different climate changes projected by the ECHAM4, HadCM2 and the CGCM1 models (Carter *et al.* 2001) is shown in Table 15. It is clear that there is a wide range of results, with ECHAM4 projecting losses at the lower end of the other two model estimates. For the developing countries as a group ECHAM4 projects a potential cereal production increase of 23 million tons per year affecting 3.7 billion people. The other two models project losses in the range of 63 to 226 million tonnes per year, affecting 3.3 to 5.5 billion people respectively.

Table 12 - Global Mean Temperature increase for ECHAM4 Scenarios

ECHAM4	2020s °C above 1861-1890	2050s °C above 1861-1890	2080s °C above 1861-1890
Greenhouse gas only	1.5	2.5	3.0
Greenhouse gases plus aerosols	1.3	1.7	NA

Note: Estimated with data from the IPCC DDC web site[104] for the ECHAM 4 scenarios for increases with respect to 1961-1990 average and converted to the 1861-1890 reference period using the observed increase in global mean temperature from this period to 1961-1990 (Folland *et al.* 2001), an offset of about 0.3°C. The scenario with aerosols was used only for the 2020s and not for other time periods in the GAEZ study.

Table 13 - Developing Country Changes in Rain Fed Cereal Production Potential 2080s for Three Climate Models

Climate Model	Number of countries			Projected population 2080 (billions)			Change in cereal production potential (million tons)			
	G[a]	N	L	G	N	L	G	N	L	Total
ECHAM4	40	34	43	3.1	0.9	3.7	142	–2	–117	23
HADCM2	52	27	38	3.2	1.2	3.3	207	3	–273	–63
CGCM1	25	26	66	1.1	1.1	5.5	39	3	–268	–226

Notes: a. G = countries gaining +5% or more; N = small change of –5 to +5%; L = countries losing –5% or more. This tables shows the number of developing countries projected to experience gains, no change or losses in cereal production potential on current cultivated land and potentially cultivatable land in the 2080s. Source: Table 5.28, Fischer *et al.* (2002: 105). ECHAM 4 refers to the AOGCM of the Max Planck Institute for Meteorology, HadCM2 to that for the Hadley Centre in the UK and CGCM1 to that of the Canadian Climate Modelling Centre.

Discussion and Summary

It seems very likely that the pattern of some regions and countries gaining and others losing is a robust feature of the impacts of climate change over the next century. Many studies indicate that developing countries are likely to lose as a whole, relative to the developed nations. India is projected to experience significant losses, with quite large areas of current cropland losing significant productivity.

Few estimates have been made of the overall macroeconomic consequences of projected agricultural effects of climate change for developing countries. In many

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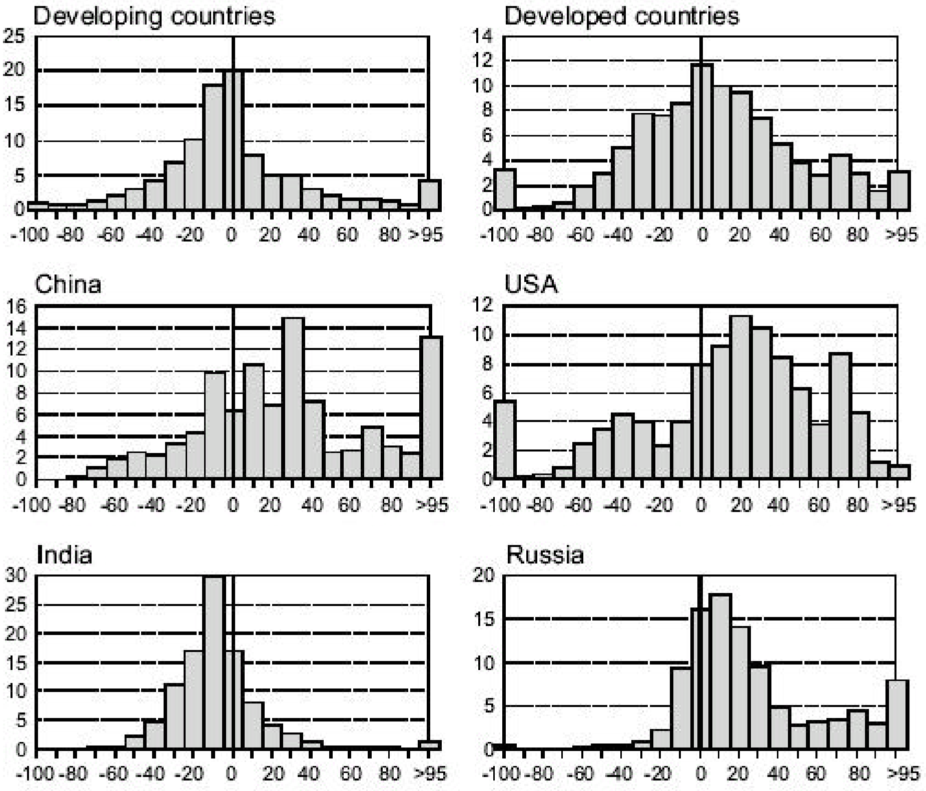
[104] http://ipcc-ddc.cru.uea.ac.uk/asres/scenario_home.html.

countries of Africa and Asia, the agricultural sector represents a large share of the economic activity. This share is projected to remain large over the next fifty years or so, thus grounds for concern exist about the possible impacts of macroeconomic shocks from climate change on vulnerable countries. One of the few computable general equilibrium assessments published, projected large, even "violent changes in the economic and social structure," as a consequence of climate shocks (Winters *et al.* 1998: 16). Though the basis for the study was the old GCM scenario results of Rosenzweig and Parry (1994), it does point to some major and apparently under-examined risks, particularly for African countries.

Within countries there will be regions that gain substantially and regions that lose. The results of the GAEZ study provide an insight into this issue. Figure 12 shows the relative change in productivity of cereal cropping regions for the ECHAM4 scenario in the 2080s (3^{o}C) for developed and developing countries. The specific examples of India, China, the USA and Russia are also given as an illustration of these two groups.

For the developed countries, it can be seen that whilst gains outweigh losses the regions in which losses occur represent a large fraction of the total current crop area. Although the area negatively impacted in Russia is small (the Russian case is discussed further below). Developed countries will not be immune to large effects of climate change on their agricultural sectors. As the example of Australia, cited above, indicates, warming of the order of 4^{o}C is likely to put entire regions out of production, with lesser levels of warming causing substantial declines in the west and the south.

Figure 12 - Gains and Losses in Production Potential under Climate Change



Gains and losses in cereal crop productivity in current cultivated areas under the ECHAM4 model in the 2080s. Source: Figure 5.4 of GAEZ study (Fischer *et al.* 2002: 70).

From the point of interpreting these assessments in relation to Article 2, it seems that the following points might be made:

- Warming of around 1°C produces relatively small damages when measured from the point of increased risk of hunger and/or under nourishment (around 10 million more at risk) over the next century. In this temperature range nearly all developed countries are projected to benefit, whilst many developing countries in the tropics are estimated to experience small but significant crop yield growth declines relative to an unchanged climate.
- At all levels of warming, a large group of the poor, highly vulnerable developing countries is expected to suffer increasing food deficits. It is anticipated that this will lead to higher levels of food insecurity and hunger in these countries.
- Under the Parry *et al.* (2001) analysis moving from 1°C to 2°C warming triples the number of people at risk of hunger in the 2080s.
- A 2°C warming and above, is associated with increasing risk. Under the Parry *et al.* (2001) analysis, this risk increases 4-5 fold from the 2050s to the 2080s (for the same temperature). In this temperature range many developed countries may still gain, although warning signs in the literature caution that this may not be robust for all regions or even in aggregate terms. It appears that agricultural production in developed countries is finely balanced in this

temperature range between the effects of increased temperature and changes in precipitation. The effects are very sensitive to the precipitation scenarios, which vary considerably between the GCMs. Parry *et al.* (1999) call attention to the effect of the HadCM3 scenarios, which are ‘drier’ than HadCM2 in many regions and which indicate production losses in North America, Russia and Eastern Europe.

- Two recent papers illustrate the uncertainty in this area, which is critical to the global food balance. Alcamo *et al.* (2003) find that, in relation to climate impacts on Russia, uncertainty exists as to whether agricultural production would increase. This is contrary to previous published estimates. For a global mean temperature increase of 1.3-1.5°C their crop production estimates range from a 9% reduction to a 12% gain. A new assessment was done for US agriculture by Reilly *et al.* (2003). It found a more positive aggregate response to future climate warming than previous estimates, even with very high warming levels in 2100. As with most such work, the effects of pests and of extreme events do not appear to have been evaluated and both models used in the Reilly *et al.* (2003) work are relatively ‘wet’ for North America compared to others.
- For a 2.5°C warming by the 2080s, the Parry *et al.* (1999) analysis indicates 45-55 million extra people at risk of hunger. The number at risk rises very rapidly with increasing temperature.
- With 3°C warming by the 2080s, the GAEZ study projects that a very large number of people, 3.3-5.5 billion, will be living in countries or regions expected to experience large losses in crop production potential. Results hold across a range of climate models. The Parry *et al.* (2001) work places the number at risk in this temperature range on the order 65-75 million.
- For a 3-4°C warming, the upper end of the Parry *et al.* (2001) analysis, the additional number at risk are in the range 80-90 million for the HadCM2 scenario and of the order of 125 million under the HadCM3 scenario.
- Global assessments with a full range of the most recent coupled AOGCMs have yet to be published and there appear to be no recent transient scenarios used at the global level to assess warming above 3-3.5°C warming. There are few studies at the global level that have included an estimation of the effect of changes in extreme events or El Niño frequency or intensity (Rosenzweig *et al.* 2001).

Water Resources

The impacts of projected climate change on water resources appear to be significant, with the general picture from the TAR being that existing water stressed regions are likely to be more stressed in the future as a consequence of climate change. As previously done, the summary table from the TAR Synthesis Report is reproduced below (Table 14) and indicates a wide range of effects. The focus here is on water stress, as this is a key impact projected to affect large numbers of people in the future. In addition, threshold behaviour is projected as a consequence of the interplay between climate change effects, socio-economic trends and limits to adaptation capacity (Arnell 2000; Jones 2000). From Table 14 it can be seen that for many water-distressed regions global mean temperature increases above around 1.5°C lead to decreases in water supply.

Based on the "Millions at Risk" paper of Parry *et al.* (2001) and that of Arnell *et al.* (2002), which use different stabilization levels, a short analysis of the relationship between increases in global mean temperature and the risk of water shortage is done. Table 15, from Arnell *et al.* (2002), summarizes the risks of water shortage for unmitigated emissions, and stabilization at 550 and 750 ppmv CO_2 for three different time period – 2020s, 2050s and 2080s – with the associated increase in global mean temperature above 1861-1990.[105] One of the main messages from this is that after the 2020s the number at risk rises rapidly with temperature and that reduction of the increase in temperature, at lower stabilization levels reduces the risk substantially.

One of the very interesting aspects of the result of the Parry *et al.* (2001) analysis is the way in which risk changes with the projection period. The shape of the temperature response curves in the 2050s is quite different from that in the 2080s. Risk rises rapidly with any temperature increase in the 2050s, whilst in the 2080s, risk initially rises quite slowly (Figure 11). A 1°C increase in the 2050s is associated with an impact almost ten times larger than in the 2080s, whereas the level of risk are comparable in both periods for a 2°C or higher warming (see Table 10). As temperature increases in the 2080s period from around 1.0°C above 1861-1990[106] to around 2°C, the number at risk increases about five fold. One of the major reasons for this is the increased water scarcity problem for major mega-cities in Asia estimated for this time period. Table 15 can also be cross-compared with Table 10 and with Figure 11 from the "Millions at Risk" paper of Parry *et al.* (2001), with this figure clearly showing a threshold of major increase in risk in the 2080s.

Discussion and Summary

There are several points that should be mentioned and considered when viewing the results of these assessments. Firstly, the number of people living in water stressed countries, defined as those using more than 20% of their available resources, is expected to increase substantially over the next decades irrespective of climate change. Particularly in the next few decades population and other pressures are likely to outweigh the effects of climate change (see, for example, the discussion of Vorosmarty *et al.* (2000) for the period to 2025), although some regions may be badly affected during this period (see, for example, the analysis for China for 2030 by Aiwen (2000)). In the longer term, however, climate change becomes much more important. Secondly, exacerbating factors such as the link between land degradation, climate change and water availability are in general not yet accounted for in the

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[105] The stabilization scenarios are those of Mitchell *et al.* (2000) with the estimated scenario temperatures for the three periods concerned tabulated in Table 16. Note that in the paper of Arnell *et al.* (2002) these scenarios are reproduced in Figure 3, however the figure caption may be in error where it states that the temperature increase is with respect to 1990. Examination of the Mitchell *et al.* (2000) paper indicates that the increases in Figure 3 of Arnell *et al.* (2002) are with respect to the 1961-1990 mean, a difference of about 0.3°C. In relation to water shortage such a difference in the 2080s corresponds to large changes in affected populations. For example, at 1.5°C warming (above 1861-1990) the number at risk is around 600 million. At 1.8°C warming this number increases to around 1,500 million.

[106] Note the base period of temperatures for the graph is 1961-1990 and that the offset to 1861-1990 is around 0.3°C based on Folland *et al.* (2001).

global assessments. Available studies on this issue indicate substantial negative effects for Africa (Feddema 1998; Feddema 1999; Feddema and Freire 2001). Thirdly, one should be aware that regional impacts in arid and semi-arid areas are likely to be much larger, relatively, than the aggregate estimates of global assessments may imply (see for example Ragab and Prudhomme (2002)). Finally, in relation to the results described, it must be borne in mind that the HadCM2 scenarios, the primary scenarios used in the Arnell *et al.* (2002) and Parry *et al.* (2001) work, generate much larger impacts in the 2050s than other comparable models (see Table 4-6 of section 4.5.2 of Chapter 4 of the WGII TAR: 413). Hence, although the shape of the damage functions to be seen in Figure 11 might be correct, the scale of numbers at risk could be significantly lower.

Interpreting the results discussed above from the point of view of Article 2 may imply the following:

- 1°C of warming or below may still yield high levels of additional risk, particularly in the period to the 2020s and 2050s, with this risk decreasing due to the increased economic wealth and higher adaptive capacity projected for the coming century. For the 2020s, most of the current GCMs imply a level of risk of additional number of people in water shortage regions in the range 400-800 million for around a 1°C warming.[107]
- 1.5°C of warming produces quite different but nevertheless substantial levels of risk in the different time periods under the Parry *et al.* (2001) analysis, with a peak in the 2050s at over 1,500 million, declining to around 500 million in the 2080s.
- A major threshold change in risk occurs in the Parry *et al.* (2001) analysis in moving from 1.5°C to 2-2.5°C, with the numbers rising from close to 600 million to between 2.4-3.1 billion. As explained earlier, this is driven by the water demand of megacities in Indian and China in their model.
- 2°C warming and above produces consistently very high levels of additional risk at all time periods under the HadCM2 scenarios. The range of risk for the current array of models in the 2050s is in the range 662 million to around 3 billion.
- Above 2.5°C warming the level of risk begins to saturate in the range of 3.1-3.5 billion additional persons at risk.

Clearly one of the major future risks identified in the Parry *et al.* (2001) and Arnell *et al.* (1999; 2002) work is that of increased water demand from mega-cities in India and China in the 2080s. It is not clear whether or to what extent additional water resource options would be available for these cities and hence, to what extent this finding is robust. If such a threshold does exist in reality then its resolution, absent a reduction in warming, may have broad implications for environmental flows of water in major rivers of China, India and Tibet should the mega-cities of India and China seek large scale diversion and impoundments of flows in the region.

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[107] See Table 4.6 of the WGII TAR Chapter 4: 213.

Table 14 - Water resource effects of climate change

Effect	**2025**	**2050**	**2100**
CO_2 concentration[a]	405–460 ppm	445–640 ppm	540–970 ppm
Global mean temperature change from the year 1990[b]	0.4–1.1°C	0.8–2.6°C	1.4–5.8°C
Global mean temperature change from the years 1861-1890 (average)[5]	1.0-1.7°C	1.4-3.2°C	2.0-6.4°C
Global mean sea-level rise from the year 1990[b]	3–14 cm	5–32 cm	9–88 cm
Water Resource Effects[c]			
Water supply [WGII TAR Sections 4.3.6 & 4.5.2]	Peak river flow shifts from spring toward winter in basins where snowfall is an important source of water (high confidence[d]).	Water supply decreased in many water-stressed countries, increased in some other water- stressed countries (high confidence[d]).	Water supply effects amplified (high confidence[d]).
Water quality [WGII TAR Section 4.3.10]	Water quality degraded by higher temperatures. Water quality changes modified by changes in water flow volume. Increase in saltwater intrusion into coastal aquifers due to sea-level rise (medium confidence[d]).	Water quality degraded by higher temperatures (high confidence[d]). Water quality changes modified by changes in water flow volume (high confidence[d]).	Water quality effects amplified (high confidence[d]).
Water demand [WGII TAR Section 4.4.3]	Water demand for irrigation will respond to changes in climate; higher temperatures will tend to increase demand (high confidence[d]).	Water demand effects amplified (high confidence[d]).	Water demand effects amplified (high confidence[d]).
Extreme events [WGI TAR SPM; WGII TAR SPM]	Increased flood damage due to more intense precipitation events (high confidence[d]). Increased drought frequency (high confidence[d]).	Further increase in flood damage (high confidence[d]). Further increase in drought events and their impacts.	Flood damage several-fold higher than “no climate change scenarios.”

No climate policy interventions. Note: Refer to notes a-d accompanying Table 7 above. Source: Table 3.4 of IPCC TAR SYR: 72.

Table 15 - Population with Potential Increase in Water Stress

Year or period	No climate change [a] (Millions)	Unmitigated emissions (Millions)	Temperature above 1861-1890	S750 (Millions)	Temperature above 1861-1890	S550 (Millions)	Temperature above 1861-1890
1990	1710		0.6°C		0.6°C		0.6°C
2020s	5022	338–623	1.2°C	242	1.0°C	175	0.8°C
2050s	5914	2209–3195	2.2°C	2108	1.5°C	1705	1.2°C
2080s	6405	2831–3436	3.2°C	2925	2.0°C	762	1.5°C

Source: Table II of Arnell *et al.* (2002): 424 with scenario temperatures added (see Table 16).

[a] Number of people in countries using more than 20% of their resources. Increase in stress means a reduction in resource availability by more than 10%. The range in estimates for the unmitigated scenario reflects the range between the four ensemble partners.

Table 16 - Scenario Temperatures

Scenario	2020s °C above 1861-1890 average	2050s °C above 1861-1890 average	2080s °C above 1861-1890 average
IS92a	1.2	2.2	3.2
S750	1.0	1.5	2.0
S550	0.8	1.2	1.5

Note: Estimated temperatures for the IS92a, stabilization at 550 and 750 ppmv CO_2 scenarios from HadCM2 model Mitchell *et al.* (2000) used in the study by Arnell *et al.* (2002). See footnote 105.

Socio-economic damages

Owing to the large range of results in the literature, as well methodological issues such as accounting for risk aversion and distributional issues, the IPCC TAR found it difficult to reach very firm conclusions on the quantitative estimation of the socio-economic damages of climate change.
Table 17 reproduces the relevant summary table from the IPCC TAR SYR. Some of the key, heavily negotiated, agreed[108] conclusions are repeated verbatim below:[109]

> "The effects of climate change are expected to be greatest in developing countries in terms of loss of life and relative effects on investment and the economy. For example, the relative percentage damages to GDP from climate extremes have been substantially greater in developing countries than in developed countries." (WGII TAR SPM Section 2.8)
>
> "More people are projected to be harmed than benefited by climate change, even for global mean temperature increases of less than a few degrees (low confidence)."
>
> "Notwithstanding the limitations expressed above, based on a few published estimates, increases in global mean temperatures would produce net economic losses in many developing countries for all magnitudes of warming studied (low confidence), and losses would be greater in magnitude the higher the level of warming (medium confidence)."
>
> "In contrast an increase in global mean temperature of up to a few degrees Celsius would produce a mixture of economic gains and losses in developed countries (low confidence), with economic losses for larger temperature increases (medium confidence)."[110]

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[108] The texts of Summaries for Policy Makers are negotiated line by line by Governments and, in effect, usually reflect a consensus between different governmental views and those of the IPCC Convening Lead Authors present. It has rarely happened that the IPCC Chair has permitted a conclusion to be changed by governments to the extent that CLAs present can no longer associate themselves with it. More commonly contested conclusions are reduced in specificity, generalized or plain 'watered down' under pressure from governments who disagree with the drafts prepared by the lead authors and reviewed three times by governments and experts. In the case of the conclusions cited here some governments vigorously contested the drafts prepared by the Lead Authors. After lengthy negotiations the final text is different from that proposed by the Lead Authors, with the final emphasis on the mixture of economic losses and gains reflecting a feeling that presenting net aggregate figures was misleading as it did not say who would benefit and who would lose. From the studies cited, it was clear than even for low levels of warming there were developed countries that would suffer net losses and within countries significant sectors would lose whilst others gained.

[109] Quotes are from the TAR SYR unless noted otherwise.

[110] The proposed text from the lead authors originally attempted to include temperatures in this statement, however as noted earlier such references were deleted. Originally the text said: "In many developed countries, net economic gains are projected for global mean temperature increases up to roughly 2°C (medium confidence). Mixed or neutral net effects are projected in

> "The projected distribution of economic impacts is such that it would increase the disparity in well-being between developed countries and developing countries, with disparity growing for higher projected temperature increases (medium confidence). The more damaging impacts estimated for developing countries reflects, in part their lesser adaptive capacity relative to developed countries [7.2.3]" (WGII TAR SPM Section 2.8).

Chapter 19 of IPCC TAR WGII has a very useful discussion on the estimation of economic damages and benefits to which the reader is referred,[111] some of the key points are:

- Impact estimates are highly sensitive to inequity aversion or risk aversion assumptions, with the greater the aversion to risk or inequity the higher the estimated damage costs (see, for example, Tol (2001)).
- Current market estimates of damage are lower than in the Second Assessment Report due to the inclusions of better adaptation estimates.
- Non-market damages are likely to be quite high.
- Global aggregate estimates are very sensitive to the weights given to different regions (see, for example, the discussions in Fankhauser and Tol (1997; 1998) and Azar (1999)).
- The shape of the climate damage function in relation to future temperature change is quite uncertain. Whether or not the damages from climate change rise rapidly or slowly with increasing temperature is a quite fundamental concern for policy.

Figure 13 below (reproduced from IPCC WGII TAR Chapter 19) shows a range of estimates for global aggregate damages and gives an impression of the uncertainty and divergence in global aggregate damage estimates. The curve of Mendelsohn *et al.* (2000) is essentially flat up to a global mean warming of 6°C warming, which is quite interesting given that this a change in magnitude the same as, but 60-120 times faster than, the transition from a full glacial to interglacial climate. Tol's curves show quite different shapes depending on the equity assumptions underlying the global aggregation of regional damage estimates (Tol 2002). Equity weighted estimates almost completely eliminate the substantial benefits for a warming in the range of 1-3°C, with net damages above about 1.5°C warming and a roughly linear increase in damages thereafter. The Nordhaus and Boyer (2000) curves are quite non-linear and show steepening damages as temperature rises.

Another way to look at this issue is with respect to the question of what are the ranges of temperature associated with reductions in world GDP. From the examination of the Nordhaus and Tol model outcomes (depicted in Figure 13), it is estimated that a 1% reduction may occur within a 2.5-3.6°C warming or possibly never, a 2% reduction for temperatures between 3.2-6.5°C or possibly never and a 5% reduction for temperature increases between 4.6-5.6°C.

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developed countries for temperature increases in the approximate range of 2 to 3°C, and net losses for larger temperature increases (medium confidence)." Whilst the confidence interval placed on the first conclusion was changed after referral back to the original literature, the temperature references were changed only to reflect the decision described in footnote 98.

[111] See IPCC TAR WGII Chapter 19: 941-5.

The pattern of regional impacts seems to have greater consistency than the global aggregates. Most of these studies show that Africa and India lose significantly from a small warming. Tol (2002) estimates an African loss of about 4% of GDP for a 1°C warming (over 1990) and about a 1.7% loss for India.[112] Similarly Nordhaus and Boyer (2000) indicate substantial losses (4-5%) for their benchmark warming of 2.5°C (inferred to be above 1900). In one out of two broad scenarios, Mendelsohn *et al.* (2000) estimate smaller losses for a 2°C warming (0.25-0.5%) for India, and in the range 0.5-1% loss, or greater for much of Africa. Their other scenarios find benefits in most places. It is worth noting that under their model, the very large benefits to Russian agriculture computed for a 2°C warming tend to be decisive in determining the global aggregate effects at this level of warming.

Finally, it appears that very few analyses have been conducted across the full range of uncertainties in the parameters and assumptions underlying model based estimates of climate damages and benefits. Recently Tol (2003) explored this issue, publishing a Monte Carlo simulation for his FUND model, which was used to compute the damage curve described above. He found a non-zero probability of very negative effects in some regions. It is worth repeating some of his own discussion, coming, as it does, from one of the more prominent modellers in this area:

> "Suppose that climate change is worse than expected. Suppose that the impacts of climate change are worse than expected. Suppose that a lot of money needs to be spent on building sea walls and curing malaria. Suppose that agricultural yields are disappointing and storms and floods damage roads and houses. In a fragile economy, this means that economic growth is halted. It means that investment and past savings are diverted from enhancing productivity and preventing further havoc to restoring damage. It means that the economy grows more fragile. It means that climate change can do even more damage, making the economy yet more fragile" (281).
>
> "Can climate change cause a poverty trap? Recurring natural disasters can definitely contribute to poverty trap … Estimates of the impact of climate change suggest that they can be worth a couple of percent of GDP, particularly in poor regions. Climate change seems likely to cause poverty traps in some places, and with some non-negligible change at a regional scale" (281).

Discussion and Summary

From the point of view of Article 2 and its interpretation, it seems that the tentative conclusions one might draw from the above would include:

- For a 1°C warming a significant number of developing countries appear likely to experience net losses, which range as high as a few % of GDP, whilst most developed countries are likely to experience a mix of damages and benefits, with net benefits predicted by a number of models.
- For a 2°C warming the net adverse effects projected for developing countries appear to be more consistent and of the order of a few to several percentage points of GDP depending upon the model. Regional damages for some

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[112] See Table VII of Tol (2002).

developing countries and regions, particularly in Africa, may exceed several percentage points of GDP.

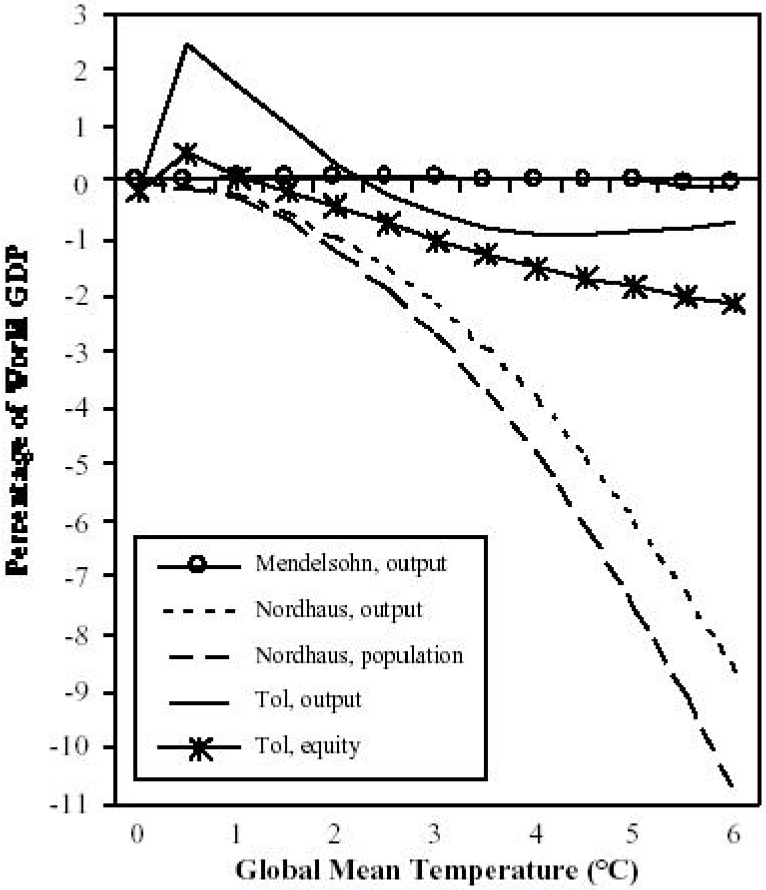
- Above 2°C the likelihood of global net damages increases but at a rate that is quite uncertain. Apart from the results of Mendelsohn et al (2000), the effects on several developing regions in the literature appear to be in the range of 3-5% for a 2.5-3°C warming, if there are no adverse climate surprises. Global damage estimates are in the range of 1-2% for 2.5-3°C warming, with some estimates increasing substantially with increasing temperature. If major identified risks such as thermohaline shutdown or non-linear feedbacks in the carbon cycle eventuate, then the damages could be very high. Regionally, there is very little evidence that the pattern of increasing damages to many developing countries would reverse and most indicates a continuing increase in net damages. Africa seems to be consistently amongst the regions with high to very high projected damages.

Table 17 - Other market sector effects of climate change

Effects	**2025**	**2050**	**2100**
CO_2 concentration[a]	405–460 ppm	445–640 ppm	540–970 ppm
Global mean temperature change from the year 1990[b]	0.4–1.1°C	0.8–2.6°C	1.4–5.8°C
Global mean temperature change from the years 1861-1890 (average)[5]	1.0-1.7°C	1.4-3.2°C	2.0-6.4°C
Global mean sea-level rise from the year 1990[b]	3–14 cm	5–32 cm	9–88 cm
Other Market Sector Effects[c]			
Energy [WGII TAR Section 7.3]	Decreased energy demand for heating buildings (high confidence[d]). Increased energy demand for cooling buildings (high confidence[d]).	Energy demand effects amplified (high confidence[d]).	Energy demand effects amplified (high confidence[d]).
Financial sector [WGII TAR´Section 8.3]		Increased insurance prices and reduced insurance availability (high confidence[d]).	Effects on financial sector amplified.
Aggregate market effects[e] [WGII TAR Sections 19.4-5]	Net market sector losses in many developing countries (low confidence[d]). Mixture of market gains and losses in developed countries (low confidence[d]).	Losses in developing countries amplified (medium confidence[d]). Gains diminished and losses amplified in developed countries (medium confidence[d]).	Losses in developing countries amplified (medium confidence[d]). Net market sector losses in developed countries from warming of more than a few °C (medium confidence[d]).

No climate policy interventions. Refer to footnotes a-d accompanying Table 7 and footnote e. Aggregate market effects represent the net effects of estimated economic gains and losses summed across market sectors such as agriculture, commercial forestry, energy, water, and construction. The estimates generally exclude the effects of changes in variability and extremes, do not account for the effects of different rates of change, and only partially account for impacts on and services that are not traded in markets. These omissions are likely to result in underestimates of economic losses and overestimates of economic gains. Estimates of aggregate impacts are controversial because they treat gains for some as cancelling losses for others and because the weights that are used to aggregate across individuals are necessarily subjective. Source: Table 3-5 of IPCC TAR SYR: 74.

Figure 13 - Climate Damages or Benefits as a Function of Temperature



Note: This figure is drawn from figure 19-4 IPCC WGII TAR Chapter 19 and shows several examples of aggregated global monetary damage functions as a percentage of world GDP from three prominent economists. 'Output', 'population' and 'equity' refer to the weightings used in making the aggregate assessments. See text for references. Note that temperature increase is with respect to 1990. One needs to add 0.6°C to convert to an estimate of increases above 1861-1890.

4. Summary and Conclusions

The results of the foregoing analysis are difficult to synthesize into a simple picture without losing many of the caveats and qualifications required. Nevertheless an attempt will be made here but the reader is urged to also examine the underlying arguments in the preceding sections. The summary here will focus on conclusions that can be drawn in relation to projected impacts at different levels of global mean temperature increase above 1861-1890, which is here used as the proxy for the pre-industrial climate. Bear in mind that there has been a global mean warming of around 0.6oC since that time.

Ecosystems impacts

Impacts on coastal wetlands

- Below a 1°C increase the risk of damage is low for most systems.

- Between 1 and 2°C warming moderate to large losses appear likely for a few vulnerable systems. Of most concern are threats to the Kakadu wetlands of northern Australia and the Sundarbans of Bangladesh, both of which may suffer 50% losses at less than 2°C and are both on the he UNESCO World Heritage List.

- Between 2-3°C, it is possible that the Mediterranean, Baltic and several migratory bird habitats in the US experience a 50% or more loss. In this range it seems likely that there could be the complete loss of Kakadu and the Sundarbans.

A key issue is the inertia of sea level rise, which makes the assignment of risk to different temperature levels misleading. Should, for example, sea level rise by 30cm in the coming decades to a century (threatening Kakadu for example), the thermal inertia of the ocean is such that an ultimate sea level rise of 2-4 times this amount may be inevitable even if temperature stops rising. The prognoses for wetlands in this context is not clear, as many damages are linked to the rate of sea level rise compared to the accretion and/or migratory capacity of the system. A major determinant of the latter will be human activity adjacent to, or in the inland catchments of the wetland system.

Impacts on animal species

- Below 1°C warming, there appears to be a risk of extinction for some highly vulnerable species in south-western Australia and to a lesser extent in South Africa. Range losses for species such as the Golden Bower bird in the highland tropical forests of North Queensland Australia and for many animal species in South Africa are likely to become significant and observable.

- Between 1 and 2°C warming, large and sometimes severe impacts appear possible for some Salmonid fish habitats in the USA, the Collared Lemming in Canada, many South African animals and for Mexico's fauna. Extinctions in the Drayandra forest of south-western Australia seem very likely. There is an increasing risk of this in South Africa, Mexico for the most vulnerable species and for especially vulnerable highland rainforest vertebrates in North Queensland, Australia. Mid summer ice reduction in the Arctic ocean seems likely to be at a level that would cause major problems for polar bears at least at a regional level.

- Between 2-3°C large to severe impacts appear likely and there are several predicted extinctions in the literature. These include towards the upper end of this temperature increase range several Hawaiian Honeycreepers, the Golden Bower bird of the highland tropical rainforest of North Queensland Australia and four species in South Africa. In general large impacts are projected for Mexican fauna, many South African animals, the Collared Lemming in the Arctic (which would have broad implications for arctic ecosystems), Salmonid fish in Wyoming. Perhaps the most worrying projection is for the "catastrophic loss" of endemic rainforest vertebrates of the highland rainforests of North Queensland, Australia. These would be experiencing rapidly increasing losses of their core environments in the upper end of this warming range.

- Above 3oC, large impacts begin to emerge for waterfowl populations in the Prairie Pothole region in the USA. In the Arctic the collared lemming range is reduced by 80%, very large reductions are projected for Arctic sea ice cover particularly in summer that is likely to further endanger polar bears. Extinction of the Golden Bower bird is predicted in this temperature range and there seems to be a very high likelihood that large numbers of extinctions would occur amongst the 65 endemic vertebrates of the highland rainforests of North Queensland, Australia. In Mexico very severe range losses for many animals are projected, as is the case also in South Africa, with Kruger national park projected to lose two thirds of the animals studied.

Impacts on ecosystems

- Between present temperatures and a 1°C increase, three ecosystems appear to be moving into a high risk zone - coral reefs, the highland tropical forests in Queensland, Australia, the Succulent Karoo in South Africa. Increased fire frequency and pest outbreaks may cause disturbance in boreal forests and other ecosystems.

- Between 1-2°C the Australian highland tropical forest, the Succulent Karoo biodiversity hot spot, coral reef ecosystems and some Arctic and alpine ecosystems are likely to suffer large or even severe damage. The Fynbos of South Africa will experience increased losses. Coral reef bleaching will likely become much more frequent, with slow or no recovery, particularly in the Indian Ocean south of the equator. Australian highland tropical forest types, which are home to many endemic vertebrates, are projected to halve in area in this range. The Australian alpine zone is likely to suffer moderate to large losses and the European Alpine may be experiencing increasing stress. The substantial loss of Arctic sea ice likely to occur will harm ice dependent species such as the polar bears and walrus. Increased frequency of fire and insect pest disturbance is likely to cause increasing problems for ecosystems and species in the Mediterranean region. Moderate to large losses of boreal forest in China can be expected. Moderate shifts in the range of European plants can be expected and in Australia moderate to large number of Eucalypts may be outside out of their climatic range.

- Between 2-3°C coral reefs are projected to bleach annually in many regions. At the upper end of this temperature band, the risk of eliminating the Succulent Karoo and its 2800 endemic plants is very high. Moderate to large reductions in the Fynbos can be expected, with the risk of significant extinctions. Australian mainland alpine ecosystems are likely to be on the edge of disappearance. European alpine systems will at or above their anticipated tolerable limits of warming with some vulnerable species close to extinction. Severe loss of boreal forest in China is projected and large and adverse changes are also projected for many systems on the Tibetan plateau. Large shifts in the range of European plants seem likely and a large number of Eucalypt species may expect to lie outside of their present climatic range. Moderate to large effects are projected for Arctic ecosystems and boreal forests. Within this temperature range there is a likelihood of the Amazon forest suffering potentially irreversible damage leading to its collapse.

Agriculture and food security impacts

Many studies indicate that developing countries are likely to lose as a whole, relative to the developed nations. India, for example, is projected to experience significant losses, with quite large areas of current cropland losing significant productivity. At all levels of warming, a large group of the poor, highly vulnerable developing countries is expected to suffer increasing food deficits. It is anticipated that this will lead to higher levels of food insecurity and hunger in these countries. Developed countries will not be immune to large effects of climate change on their agricultural sectors.

- Warming of around 1°C produces relatively small damages when measured from the point of increased risk of hunger and/or under nourishment (around 10 million more at risk) over the next century. In this temperature range nearly all developed countries are projected to benefit, whilst many developing countries in the tropics are estimated to experience small but significant crop yield growth declines relative to an unchanged climate.
- Warming from 1°C to 2°C warming triples the number of people at risk of hunger in the 2080s.
- Between 2-3oC warming the risk of damage begins to increase significantly. Whilst developing countries may still gain in this temperature range the literature indicates that production is finely balanced in this temperature range between the effects of increased temperature and changes in precipitation. ‘Drier’ models show losses in North America, Russia and Eastern Europe whereas ‘wetter’ models show increases. One study shows rapidly rising hunger risk in this temperature range with 45-55 million extra people at risk of hunger by the 2080s for 2.5oC warming which rises to 65-75 million for a 3oC warming. Another study shows that a very large number of people, 3.3-5.5 billion, may be living in countries or regions expected to experience large losses in crop production potential at 3oC warming.
- For a 3-4°C warming, in one study the additional number at risk of hunger is estimated to be in the range 80-125 million depending on the climate model. In Australia a warming of the order of 4°C is likely to put entire regions out of production, with lesser levels of warming causing substantial declines in the west and the south.

Water impacts

The number of people living in water stressed countries, defined as those using more than 20% of their available resources, and is expected to increase substantially over the next decades irrespective of climate change. Particularly in the next few decades population and other pressures are likely to outweigh the effects of climate change, although some regions may be badly affected during this period. In the longer term, however, climate change becomes much more important. Exacerbating factors such as the link between land degradation, climate change and water availability are in general not yet accounted for in the global assessments.

- Around 1°C of warming may entail high levels of additional risk in some regions, particularly in the period to the 2020s and 2050s, with this risk decreasing due to the increased economic wealth and higher adaptive capacity projected for the coming century. For the 2020s the additional number of people in water shortage regions is estimate to be in the range 400-800.
- Between 1-2°C warming the level of risk appears to depend on the time frame and assumed levels of economic development in the future. One study for the middle of this temperature range has a peak risk in the 2050s at over 1,500 million, which declines to around 500 million in the 2080s.
- Over 2oC warming appears to involve a major threshold increase in risk. One study shows risk increasing for close to 600 million people at 1.5oC to 2.4-3.1 billion at around 2.5°C. This is driven by the water demand of mega-cities in India and China in their model. In this study the level of risk begins to saturate in the range of 3.1-3.5 billion additional persons at risk at 2.5-3oC warming.

One of the major future risks identified by two studies is that of increased water demand from mega-cities in India and China. It is not clear whether or to what extent additional water resource options would be available for these cities and hence, to what extent this finding is robust. This may have broad implications for environmental flows of water in major rivers of China, India and Tibet should the mega-cities of India and China seek large-scale diversion and impoundments of flows in the region.

Socio-economic effects

- For a 1°C warming a significant number of developing countries appear likely to experience net losses, which range as high as a few % of GDP. Most developed countries are likely to experience a mix of damages and benefits, with net benefits predicted by a number of models.
- For a 2°C warming the net adverse effects projected for developing countries appear to be more consistent and of the order of a few to several percentage points of GDP depending upon the model. Regional damages for some developing countries and regions, particularly in Africa, may exceed several percentage points of GDP.
- Above 2°C the likelihood of global net damages increases but at a rate that is quite uncertain. The effects on several developing regions appear to be in the range of 3-5% for a 2.5-3°C warming, if there are no adverse climate surprises. Global damage estimates are in the range of 1-2% for 2.5-3°C warming, with some estimates increasing substantially with increasing temperature.

If major identified risks such as thermohaline shutdown or non-linear feedbacks in the carbon cycle eventuate, then the damages could be very high. Regionally, there is very little evidence that the pattern of increasing damages to many developing countries would reverse and most indicates a continuing increase in net damages. Africa seems to be consistently amongst the regions with high to very high projected damages.

Conclusions

It seems clear from this partial review of the available literature that the risks arising from projected human induced climate change increase significantly with increasing temperature. Below a 1oC increase the level of risk are low but in some case not insignificant particularly for highly vulnerable ecosystems. In the 1-2oC-increase range risks across the board increase significantly and at a regional level are often substantial. Above 2oC the risks increase very substantially involving potentially large extinctions or even ecosystem collapses, major increases in hunger and water shortage risks as well as socio-economic damages, particularly in developing countries.

5. Appendix: Temperature scale

The analysis in this paper focuses on determining the projected impacts of climate change associated with increases above the pre-industrial average global temperature (approximated by 1851-1880 average). One of the main reasons for using this baseline is that the temperature limit of the WBGU tolerable window is specified with respect to the pre-industrial atmosphere.

In most cases the IPCC has used the base year of 1990 for its analyses of projected effects, whereas the literature uses a variety of different base periods or years (for example, the 1961-1990 climatology is often used). By and large the projected temperature increases presented in the TAR are with respect to 1990, which is thought to be about 0.6°C warmer than the pre-industrial average (Folland *et al.* 2001). Most contemporary GCM scenarios start from the pre-industrial period and hence their changes in climate, in effect, are with respect to the assumed state of the pre-industrial atmosphere and climate system. Often, the changes in climate statistics computed by these models are reported with the respect to a standard 30-year mean climatology of 1961-1990. A thirty-year averaging period is used as this eliminates most of the year-to-year variability in global mean temperature. Many recent impact studies are based on the change in the GCM climatology between a future period e.g. 2050s (30 year average around 2050) and the 1961-1990 average climatology from the model, applied to the observational mean of the 1961-1990 period. The 1961-1990 average temperature is about 0.3°C less than the 1990 global average temperature.

To further complicate matters, rather than specify a temperature range for an impact many of the IPCC TAR assessments from Working Group II are reported with respect to a temperature range classification of “small” (less than 2°C above 1990), medium (2-3°C above 1990) and “large” (greater than 3°C above 1990).[113] It should be noted with respect to the latter that the IPCC states that a “2°C warming from 1990 to 2100 would be a magnitude of warming greater than any that human civilization has ever experienced. Thus, “small” does not necessarily mean negligible.”[114]

As a consequence of these and other factors, there often needs to be a conversion from the reported impact or effect (which may also be estimated with respect to a local temperature increase against a different base period) to a scale with respect to pre-industrial. Table 18 outlines the overall scales used to convert the different base periods or classifications mentioned above to a pre-industrial temperature increase.

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[113] It should be noted that this was in response to pressure principally from the Saudi Arabian delegation at the IPCC Working Group II Plenary in Geneva in February of 2001 and was resisted by most of the lead authors of the relevant chapters of Working Group II. In the end, after many hours of negotiation, the contact group chair, then IPCC Chair Bob Watson, concluded that a consensus could only be reached with the adoption of the above classification.

[114] Chapter 19 of the IPCC WGII TAR: 957.

Table 18 - Global Temperature Scales used in this Report

Increase above pre-industrial temperature °C	Increase above 1990 temperature °C	Above 1961-1990 average temperature °C	IPCC TAR classification
0.0	-0.6	-0.3	Small
1.0	0.4	0.7	Small
1.6	1.0	1.3	Small
2.0	1.4	1.7	Small
2.6	2.0	2.3	Medium
3.0	2.4	2.7	Medium
3.6	3.0	3.3	Medium
4.0	3.4	3.7	Large
4.6	4.0	4.3	Large
5.0	4.4	4.7	Large
5.6	5.0	5.3	Large
6.0	5.4	5.7	Large
6.6	6.0	6.3	Large
7.0	6.4	6.7	Large
7.6	7.0	7.3	Large
8.0	7.4	7.7	Large

Placing sea level rise on a common scale is an altogether more complex task and there has been no attempt here to do this in a general sense. Each example where an impact is linked to a specific sea level rise is taken on its own and where possible converted to global mean temperature range using available information as described in a footnote or textual explanation.

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