Relationship between increases in global mean temperature and impacts on ecosystems, food production, water and socio-economic systems

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Abstract

This paper attempts to associate different levels of global mean surface temperature increase and/or sea level rise with specific impacts and risks for species, ecosystems, agriculture, water and socio-economic damages compared to pre-industrial global mean temperature. It is found that that the risks arising from projected human induced climate change increase significantly and systematically with increasing temperature. Below a 1oC increase the level of risks are generally low but in some case not insignificant, particularly for highly vulnerable ecosystems and/or species. Above a 1oC increase risks increase significantly, often rapidly for highly vulnerable ecosystems and species. 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 numbers of extinctions or even ecosystem collapses, major increases in hunger and water shortage risks as well as socio-economic damages, particularly in developing countries.

1 Introduction

The ultimate objective of the United Nations Framework Convention on Climate Change, specifies in its Article 2 that the stabilization of greenhouse gas concentrations at levels that "would prevent dangerous anthropogenic interference with the climate system" 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" [*1*]. In this paper the relationship between increases in global mean temperature and the latter elements mentioned in Article 2 are explored in order to cast light on the risks posed by climate change.

2 Method

An extensive review of the literature on the impacts of climate change on ecosystems and species, food production, water and damages to economic activity has been undertaken and studies analysed to determine relationships between global mean temperature and the risks identified in each work [*2*][1]. Studies were drawn almost always from the peer reviewed literature or work that was reviewed for the IPCC Third Assessment Report. Many different baseline climatologies and other climatic assumptions have been used in the literature. For those studies analysed all climate scenarios used were reduced to a common global mean temperature scale with respect to the pre-industrial period defined as the 1861-1890 climate using a standard methodology [*2*]. Regional temperature increases used in scenarios were converted to range of global mean temperature increases using the MAGICC 4.1/SCENGEN climate model tool [*3*]. All temperatures referred to in this paper are global mean and with respect to the pre-industrial global mean.

The results for the ecosystems and species have been mapped onto a risk scale involving five categories of risk: Less than a 5% reduction in area (or other appropriate indicator) is regarded as not significant, a 5-10% reduction is defined as small risk, a 10-20% loss as moderate, a 20-50% loss is defined as large and a severe loss is defined as more than a 50% loss of area or population.

3 Results

3.1 Species and ecosystems

Between present temperatures and a 1°C increase, at least three ecosystems appear to be moving into a high risk zone - coral reefs [*4, 5*], the highland tropical forests in Queensland, Australia [*6-8*] and the Succulent Karoo in South Africa [*9-11*]. Increased fire frequency and pest outbreaks may cause disturbance in boreal forests and other ecosystems. There appears to be a risk of extinction for some highly vulnerable species in south-western Australia [*12*] and to a lesser extent in South Africa. Range losses for species such as the Golden Bower bird in the highland tropical

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[1] The work described in this paper is described in substantial detail in this larger report

forests of North Queensland Australia and for many animal species in South Africa are likely to become significant and observable.

Between 1 and 2^{o}C warming 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 is very likely to 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 [*13, 2*] and the European Alpine may be experiencing [*14, 15*] increasing stress. The substantial loss of Arctic sea ice likely to occur [*16*] will harm ice dependent species such as the polar bears and walrus [*17*] . Increased frequency of fire and insect pest disturbance is likely to cause increasing problems for ecosystems and species in the Mediterranean region [*18-21*].. Moderate to large losses of boreal forest in China can be expected [*22*]. 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 [*23*]. Large and sometimes severe impacts appear possible for some Salmonid fish habitats in the USA [*24*], the collared lemming in Canada [*25*], many South African animals and for Mexico's fauna. There is an increasing risk of extinctions in South Africa [*26*], Mexico [*27*] for the most vulnerable species and for especially vulnerable highland rainforest vertebrates in North Queensland, Australia. Extinctions in the Dryandra forest of south-western Australia seem very likely [*12*]. 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 and 3^{o}C warming 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, substantial extinctions of endemic Alpine flora in New Zealand are projected [*28*] and European alpine systems are likely to be 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 [*29*]. 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 [*30*]. 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 [*31, 32*].

Above 3oC, large impacts begin to emerge for waterfowl populations in the Prairie Pothole region in the USA [*33*]. 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. 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.

Results of the analysis of the risks for species and ecosystems are presented graphically in the Appendix at Figure 2, Figure 3, Figure 4 and Figure 5 where detailed notes are also given on the data sources and assumptions made.

3.2 Coastal Wetlands

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.

Below a 1^{o}C increase[2] the risk of damage is low for most systems. Between 1 and 2^{o}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 [*34*] and the Sundarbans of Bangladesh [*35, 36*], both of which may suffer 50% losses at less than 2^{o}C and

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[2] Impacts at different levels of global mean temperature increase above the 1861-1890 climate state, which is here used as the proxy for the pre-industrial climate.

are both on the UNESCO World Heritage List. Between 2 and 3^{o}C warming, it is likely that the Mediterranean, Baltic and several migratory bird habitats in the US would experience a 50% or more loss [*37-39*] It also seems likely that there could be the complete loss of Kakadu and the Sundarbans.

Results of the analysis of the risks for coastal wetlands are presented graphically in the Appendix at Figure 1 where detailed notes are also given on the data sources and assumptions made.

3.3 Agriculture and food security

Warming of around 1^{o}C produces relatively small damages when measured from the point of increased risk of hunger and/or under nourishment 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 [*40*]. Above this level of change the number of people at risk of hunger increases significantly. Between 2 and 3oC warming the risk of damage begins to increase significantly [*41-44*]. 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 [*45*]. ‘Drier’ climate 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[*41, 42*]. 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 [*46*].

For a 3-4oC 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 [*42*]. In Australia a warming of the order of 4oC is likely to put entire regions out of production, with lesser levels of warming causing substantial declines in the west and the south [*47*].

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.

3.4 Water resources

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 1oC 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 million [*42*] [*48*].

Between 1-2oC 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 [*42*] [*48*].

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 2.5oC. 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 [*42, 48*].

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.

3.5 Socio-economic impacts[3]

For a 1oC 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 2oC 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 2oC 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 2.5-3oC 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.

4 Conclusions

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. Africa seems to be consistently amongst the regions with high to very high projected damages.

The results of this work provide some support for the position adopted by the European Union in 1996 aiming to limit global warming to a global mean increase of 2oC above pre-industrial levels [*51*]. It seems clear however that there are substantial risks even below this level of warming, particularly for vulnerable ecosystems and regions, which tends to confirm assessments made in the late 1980’s [*52*].

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[3] See [*40*] and relevant papers [*49, 50*]

5 Appendix Figures

5.1 Impacts on Coastal Wetlands

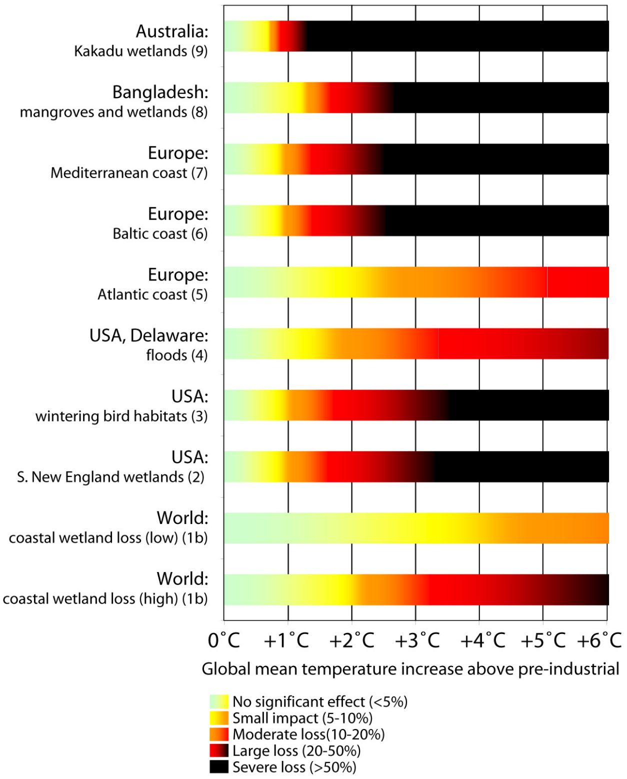

Figure 1 - Impacts on Coastal Wetlands

Notes on Figure 1:

(1a) Global assessment: High - progressive coastal wetland loss with increasing warming (22.2% for ca. 3.4oC warming). Based on the Nicholls *et al.*[*37*] assessment using the high estimate of wetland loss (22.2% in 2100 for around a 3.4°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: Low - progressive coastal wetland loss with increasing warming (5.7% for ca. 3.4oC warming). As above but for low estimates (5.7% loss by 2100) with linear extrapolation to 50%, which is likely to underestimate the rate at which this would occur.

(2) USA: Southern New England- extensive loss of wetlands if sea level rise greater than 6mm/yr: Based on Donnelly and Bertness [*53*] with assumption that a 5°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: Loss of important foraging, migratory and wintering bird habitat at four sites (20- 70% loss for ca. 2.6oC warming). Based on Galbraith *et al.* [*39*]. 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 loss 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 the temperature, which increases the temperature slightly 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 - Loss of 21% ca. 2.5-3.5oC warming - 100 year floods occurring 3-4 times more frequently. Based on Najjar *et al.* [*38*] 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.*[*37*] with a linear extrapolation of the high range 17% loss with 4.4°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°C warming.

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

(8) Bangladesh, Sundarbans: Based on Qureshi and Hobbie [*35*] and Smith *et al.* [*36*] with sea level rise and temperature relationship (for 2100) drawn from Hulme *et al.* [*54*]. 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).

Australia, Kakadu region: This estimate is highly uncertain. In the WGII TAR report Gitay *et al.* [*34*] 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.* [*54*] from the HadCM2 and HadCM3. Note that the estimate range from recent models is 1.2-3.1oC for a 30cm sea level rise.

5.2 Impacts on Animal Species

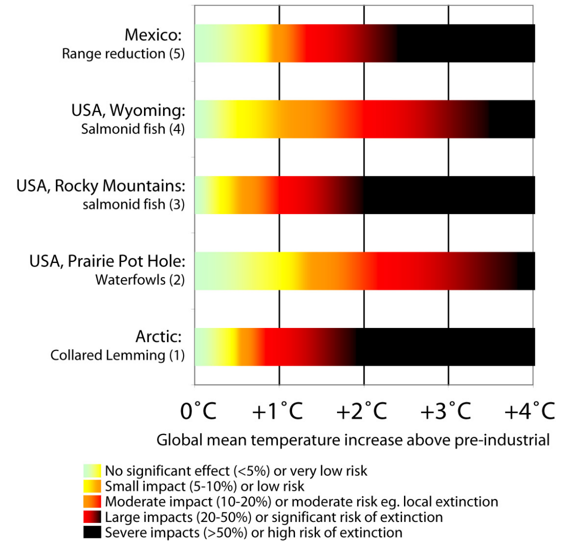

Figure 2 - Impacts on Animal Species

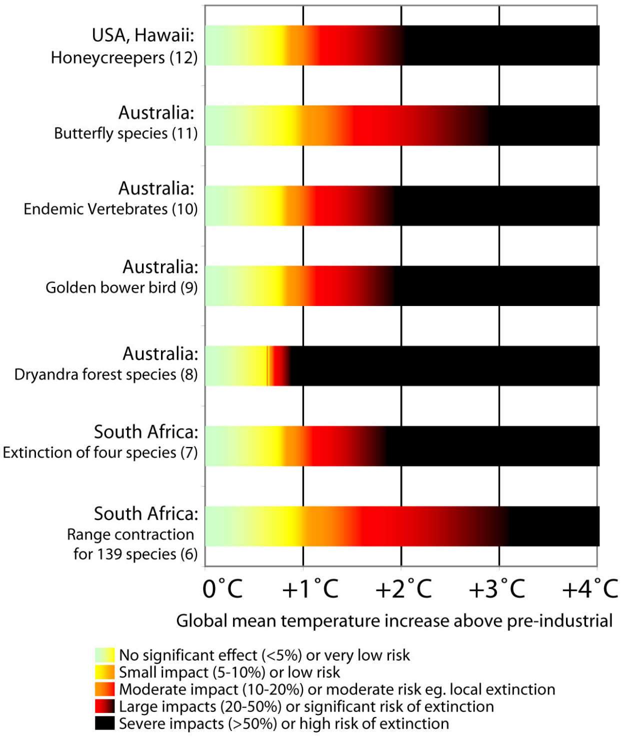

Figure 3 - Impacts on Animal Species (Continued)

Notes on Figure 2 and Figure 3:

(1) Canadian Arctic, collared lemming: Based on data in Kerr and Packer [*25*] 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 [*25*].

(2) USA, waterfowl population Prairie Pot Hole Region: Based on data in Sorenson et al. [*33*] with interpolation of data.

(3) USA, reduction of Salmonid fish habitat in Rocky Mountains: Based on data in Keleher and Rahel [*24*] 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 [*24*] with extrapolations to 50% reduction. Upscaling of temperatures as in (3).

(5) Mexico: Highly indicative interpretation of results of Peterson et al. [*27*] for range reductions. The 50% range reduction level is associated with the upper end of their warming scenario, which corresponds to 2.4oC warming above 1861-1890 and this range reduction applies to up to 19% of the entire Mexican fauna. Between present temperatures and 2.4oC 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 1.9-2.4oC warming).

(6) South Africa, range reductions of large number of animals: Highly indicative only, interpretation of results of Erasmus et al. [*26*] for range reductions in the 29 endangered species projected to experience 50% or more range reductions with a warming of 2.4oC (1.9-3.1oC range) (above 1861-1890). The scale assumes that a 50% reduction in the range of these species occurs with 3.1oC. Lower reductions are linearly scaled from 1990 temperatures.

(7) South Africa, predicted extinctions: Highly indicative only interpretation of results of Erasmus et al. [*26*] for extinctions projected for a 2.4oC increase (1.9-3.1oC range). The scale used assumes that there is a 100% chance of extinction with a 3.1oC 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 [*12*] as cited by Gitay et al. [*34*]. 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 1.1oC (above 1861-1890), and that 90% reduction occurs at 1.1oC.

(9) Australia, predicted extinction of Golden Bower bird of highland tropical forests, north east Queensland: Based on [*7*] 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 [*8*] and with similar scaling as above.

(11) Australia, large range reduction in range of butterfly species: Based in [*55*] 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 [*56*] with risk of extinction to 90% at 3.2oC

5.3 Impacts on ecosystems

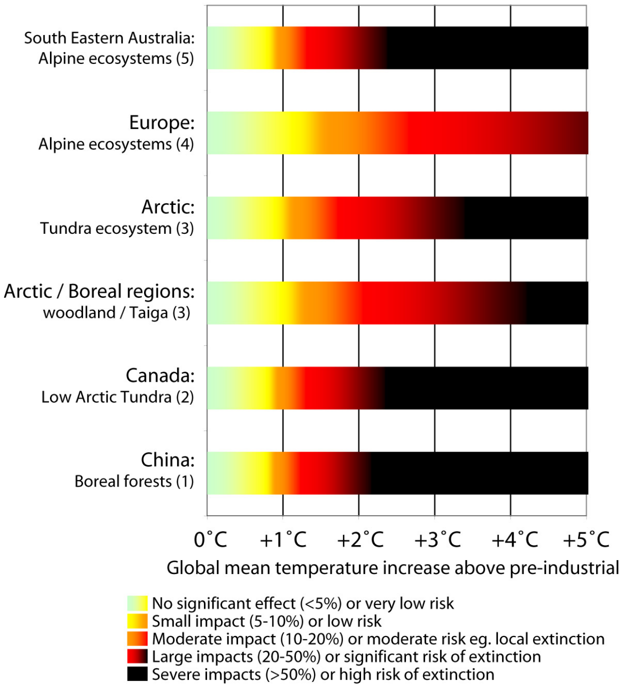

Figure 4 - Impacts on ecosystems

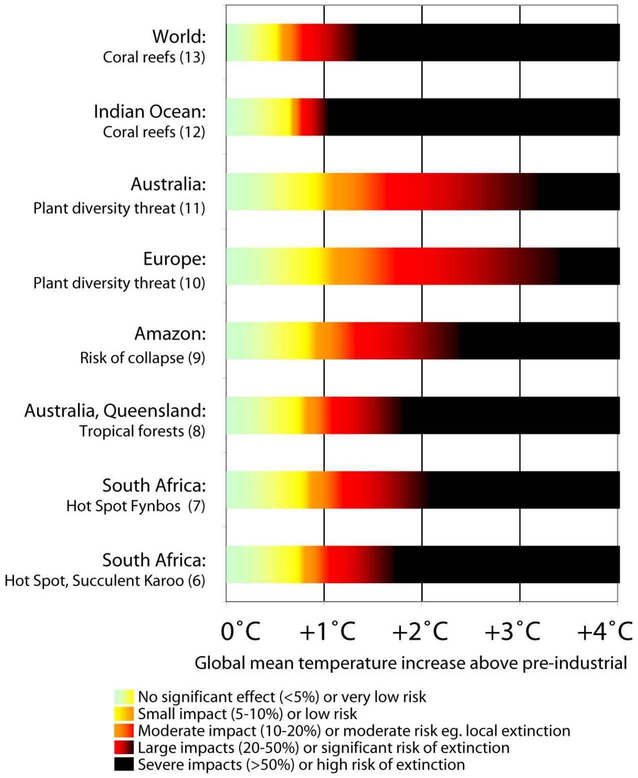

Figure 5 - Impacts on ecosystems (continued)

Notes on Figure 4 and Figure 5:

(1) Boreal forests, China: Based on Ni [*22*] 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 [*57*] 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 [*58*]

(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

(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 [*13*] 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.* [*59*] 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.* [*60*], Hilbert *et al.* [*6*], Williams *et al.* [*8*] and Hilbert *et al.* [*7*]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.* [*31*] and Cox *et al.* [*61*] 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.* [*30*] 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.* [*23*]. 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 [*4*]. 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.

6 Acknowledgements

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