AVOID 2
Can we avoid dangerous climate change?

Post-IPCC assessment of climate impacts using existing scenarios – advances in understanding

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AVOID2

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1. Introduction and scope

The aim of global climate policy is to seek to prevent dangerous climate change by reducing global emissions to a level which limits global warming to 2 °C compared with preindustrial times (Copenhagen Accord 2009).

However, there have still been surprisingly few studies which have explicitly compared socio-economic impacts under different rates of forcing and changes in global mean temperature. A great many studies have over the years compared impacts under different SRES climate scenarios (IPCC 2000) but virtually all of these have used different socio-economic scenarios for each climate scenario; they have used SRES A1b emissions with the A1 socio-economic scenario, and A2 emissions with the A2 socio-economic scenario for example. Whilst this is internally consistent, it makes it very difficult to compare socio-economic impacts for different rates of forcing. These SRES scenarios were based upon an analysis of possible future socioeconomic pathways which emerged from an expert workshop that considered how demographic, social, economic, environmental and technological aspects of our society might evolve. The climatic consequences of these futures were then derived (IPCC 2007a) and the corresponding impacts variously explored by the scientific community, whilst economists explored the potential to mitigate emissions of greenhouse gases using some of these scenarios as baselines (IPCC 2007b,c). The SRES scenarios themselves assumed no mitigation of greenhouse gas emissions. Four main types of scenarios were produced, to which no probability of occurrence was attached. In these scenarios, there were two main 'axes' of change that were considered: (a) environmental versus economic (b) a global versus regional. Hence the four scenarios may be briefly summarised as A1 (Global, economic); A2 (Regional, economic); B1 (Global, environmental); B2 (Regional, environmental).

This review summarises the available literature on the impacts of climate change at different levels of climate forcing. It builds on the literature summarised in AR5 WG2 (IPCC 2014a) and includes studies published since. It focuses on studies which have explicitly compared impacts at different levels of climate change, and concentrates on studies which have been undertaken at the global and regional scales.

There are three types of study which have can be used to explicitly to compare impacts under different levels of climate change. The first consists of the few studies which have used the new 'matrix' approach to impact assessment (*reference*), which mix and match Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs). These can be used to compare impacts under the different RCPs, for a given socio-economic future. The second set consists of a few studies which have estimated impacts for a given socio-economic future under different 'non-RCP' climate scenarios, which typically represent different amounts of mitigation (the AVOID1 studies fall into this set). The third type of study has sought to construct relationships relating impact to change in global mean temperature, for a given time period and socio-economic future.

The RCPs are designed to span a wide range of possible futures, ranging from the most extreme mitigation that any of the modelling groups could simulate in their economic models (RCP2.6), to futures without mitigation and encompass rapid large increases in greenhouse gas concentrations (RCP8.5). However, it should be borne in mind that it is still possible that concentrations might exceed these levels, so the range of RCPs should not be taken as encompassing the complete range of future outcomes. Unlike the SRES scenarios, the RCPs consider the possibility that radiative forcing could be rising or falling by 2100.

	Radiative forcing (W/m^2)	Approximate CO_2 equivalent concentration (ppm)	Rate of change in radiative forcing	Temperature rise in 2081-2100 according to IPCC WGI AR5 (IPCC 2014b) in °C
RCP8.5	8.5	1350	Rising	1.6+/-0.4
RCP6.0	6.0	850	Stabilizing	2.4+/-0.5
RCP4.5	4.5	650	Stabilizing	2.8+/-0.5
RCP2.6	2.6	450	Declining	4.3+/-0.7

Table 1. RCPs: year 2100 parameters.

The RCP concentration pathways also have matching emission data for greenhouse gases and short lived gases at a half degree latitude x longitude resolution. Information is also available about the assumed land use and land cover in these scenarios. The future land-use projections from each RCP were harmonized to ensure a smooth transition from the historical land-use data (available at http://luh.sr.unh.edu/ and based on HYDE 3.1: http://www.pbl.nl/hyde) and to compute the associated secondary (recovering) land area and all land-use transitions.

The impacts sectors examined here map on to the Reasons for Concern (RFC) that form the basis of the Figures produced in Ch. 19. AR5 (IPCC 2014a) and are included in Figure 1. The issue of uneven distribution of impacts, as well as the magnitude of impacts, is considered in the Figure. Specifically, biodiversity feeds into RFC 1 unique and threatened systems, as well as RFC 4, Global Aggregate Impacts.

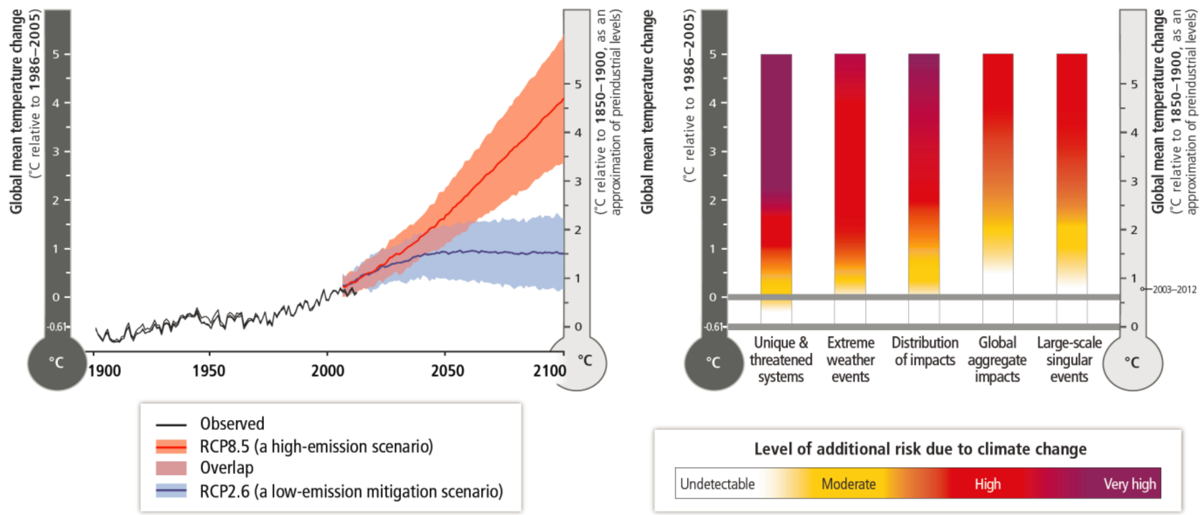

Figure 1. A global perspective on climate-related risks. Risks associated with reasons for concern are shown for increasing levels of climate change. The colour shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. Undetectable risk (white) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least medium confidence, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Purple, introduced in this assessment1, shows that very high risk is indicated by all specific criteria for key risks. Risk assessment criteria encompass large magnitude, high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation.

2. Impacts by sector

2.1 Introduction

For each impact category we provide a summary of the studies reviewed in AR5 (IPCC 2014a), the methods upon which these are based, and literature that has appeared since. We include some quantitative statements about the outputs, detailing metrics used and scenarios for which impact projections have been quantified. We also provide comments on the main uncertainties in the modelling estimates, focusing on whether model intercomparison studies have been done and what these show. Finally we comment on (e.g. social) issues left out of the modelling that might have an influence.

In each sector we sought literature that projected impacts under the four RCP scenarios detailed above, in which global temperature rise by 2081-2100 lies between 1.2 and 5.0 °C above pre-industrial (Chapter 12 in IPCC 2014b). We also included where relevant older literature based on the SRES scenarios. Whilst some quantitative information is provided in this report, detailed quantitative information will be analysed consistently across sectors (as far as the literature permits) in the next deliverable of this work package. Global temperature rises are given relative to *pre-industrial* times unless otherwise stated.

Increasing greenhouse gas concentrations lead to additional radiative forcing, which alters temperature, precipitation, and ocean circulation. Impact categories covered in this report relate to people or ecosystems affected by the resultant physical hazards that result from climate change, such as extreme weather, sea level rise, changes in rainfall patterns etc as shown in Figure 2 below. We consider freshwater, agriculture, energy, health, coastal systems and ecosystems. Each of these impact factors in turn then affects human security and the economy. There are however, important interactions between impacts sectors, which can act both locally and at a distance (not shown) (Warren, 2011; IPCC 2014a).

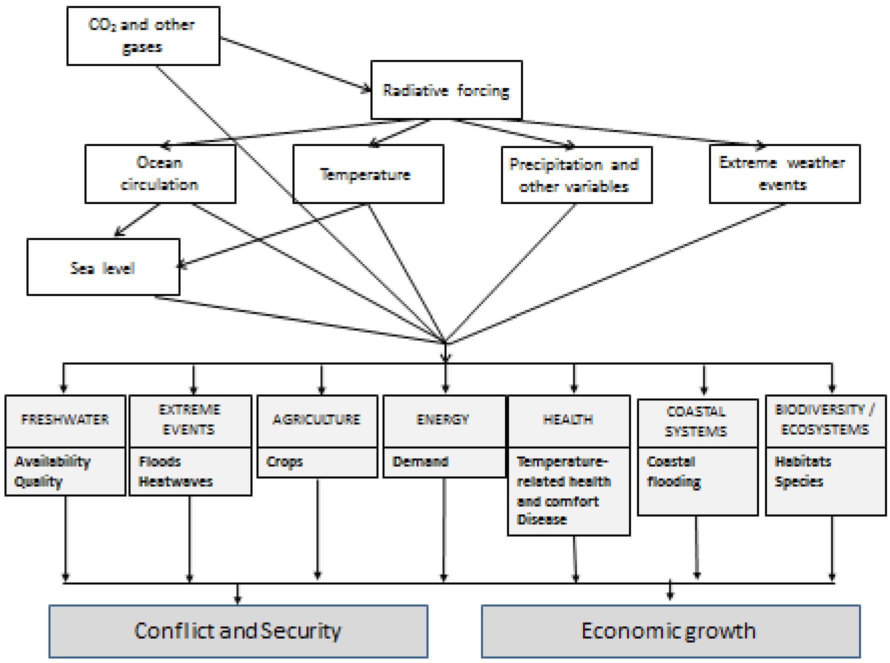

Figure 2. Drivers of climate change impacts on the economy and human security.

2.2 Water sector

Chapter 3 of IPCC WG2 AR5 (Jimenez *et al*., 2014) provides an overview of the implications of climate change for water resources. It emphasises that the vast majority of studies have been undertaken at the catchment scale, and only a few have been undertaken at regional or global scales. Most studies reported in AR5 used CMIP3/SRES climate scenarios, and only a very few used CMIP5/RCP scenarios. Table 3.2 of Chapter 3 summarises (reproduced here as Table 2.1 of the Appendix) the few studies that had, at that time, explicitly compared water resources impacts under different rates of climate change. Most of these studies used different SRES emissions profiles as proxies for different emissions policies, but a small number compared RCPs or specific emissions policies (including AVOID pathways), or used damage functions. The metrics of impact varied considerably between the studies, and included areas with specific changes in runoff, changes in irrigation requirements, and numbers of people affected by defined changes in runoff or groundwater recharge. Because the different studies have used different indicators and calculated impacts at different time horizons, it is difficult to draw generalised quantitative conclusions.

To date, 6 papers have assessed the global-scale impacts of climate change under the CMIP5/RCP climate scenarios. Five of these (Davie *et al*., 2013; Hanasaki *et al*., 2013; Portmann *et al*., 2013; Schewe *et al*., 2014 and Wada *et al*., 2013) were part of the ISI-MIP impact intercomparison project, and use between three and five CMIP5 climate models. The sixth (Arnell and Lloyd-Hughes, 2014) uses 21 CMIP5 models and all four RCPs, and was undertaken as part of the AVOID project. The range in change in water resources impacts across CMIP5 climate models is broadly similar to the range across CMIP3 models, although there may be large differences in specific regions which have not yet been investigated. Table 2.2.1 summarises three of the studies which compare impacts under RCP2.6 (strong mitigation) and RCP8.5 (no mitigation). By 2050 there is relatively little difference in impact between the two RCPs, but the difference is greater further into the 21st century.

Study	Indicator	Year	RCP2.6	RCP8.5
Portmann *et al*. (2013)	Proportion of global population exposed to a **reduction** of groundwater recharge of more than 10%. Range across 5 climate models	2080	11-37%	27-50%
Hanasaki *et al*. (2013)	Percentage of global population living in watersheds where abstractions are more than 40% of available resources, **where runoff decreases**. Range across 3 climate models	2050	27-47%	37-51%
Arnell & Lloyd-Hughes (2014)	Percentage of global population living in watersheds with less than 1000m3/capita/year, **where runoff decreases**. Range across 21 climate models.	2050	5-37%	10-37%

Table 2.2.1 Impacts of climate change on global water resources: RCP2.6 compared with RCP8.5

A major recent development, partially reported in AR5, has been the assessment of the effects of hydrological model uncertainty on estimated uncertainty in hydrological and water resources impacts, undertaken through the ISI-MIP project (Davie *et al*., 2013; Schewe *et al*., 2014). This has shown that in some regions the uncertainty in estimated impacts due to hydrological model uncertainty can be as great as, or larger than, climate model uncertainty. However, this conclusion must be regarded as tentative because (a) only 5 climate models were used to represent climate model uncertainty and (b) it is assumed that all the hydrological models are equally plausible: the intercomparison has shown, however, that much of the diversity in response is due to model components (specifically relating to evaporation) which can be easily validated.

A number of studies have also produced damage functions relating indicators of impact to change in global mean temperature. These are summarised in Figure 2.2.1. Again, these use different indicators of impact and were constructed in different ways.

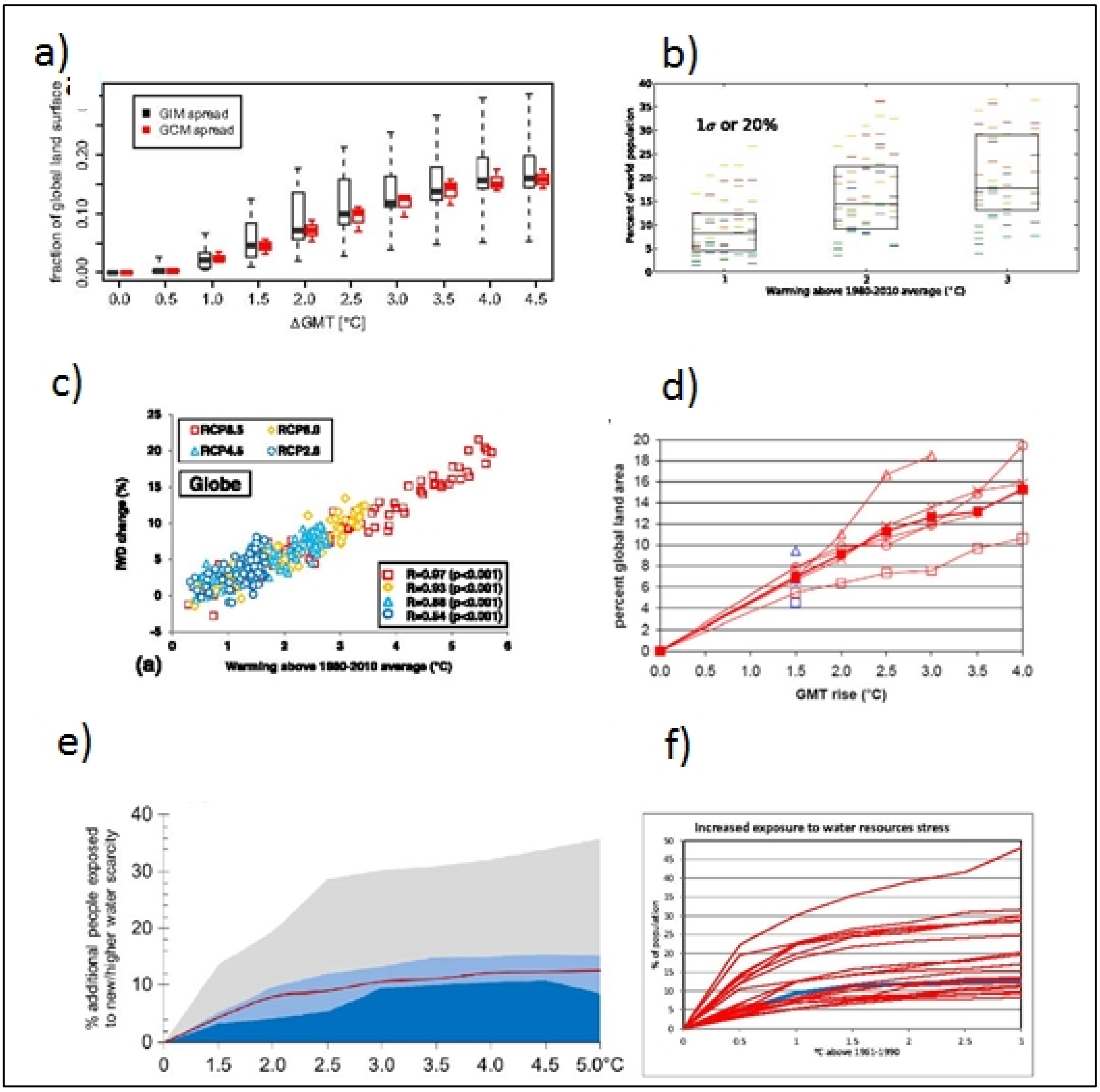

Figure 2.2.1: Damage functions relating global water resources impact to change in global mean temperature. a) proportion of land area with a ‘significant’ change in runoff (Piontek et al., 2014); b) proportion of global population exposed to a ‘significant’ change in runoff (Schewe et al., 2014); c) change in irrigation water requirements (Wada et al., 2013); d) proportion of land area with a reduction in groundwater recharge of more than 30% (Portmann et al., 2013); e) proportion of people exposed to increased water resources scarcity (Gerten et al., 2013); f) proportion of people exposed to increased water resources scarcity (Arnell et al., 2014). a), b), c) and d) show temperature change relative to 1980-2010, e) shows change relative to pre-industrial, and f) shows change relative to 1961-1990.

2.3 Extreme events

2.3.1 River floods

There have been far fewer assessments of the potential implications of climate change for global river flood risks than for global water resources. One used 21 CMIP3 climate models (Arnell and Gosling, 2014), and three have used CMIP5 simulations (Hirabayashi *et al*., 2013; Arnell and Lloyd-Hughes, 2014; Dankers *et al.*, 2014). The main headline conclusion from these studies – which, like the water resources assessments, use different indicators of impact – is that there is very considerable variability in potential impact between different climate models. Dankers *et al*. (2014) also showed, as part of the ISI-MIP exercise, that hydrological model uncertainty could be very high too, but the same caveats apply here as with the water resources assessments.

Table 2.3.1 summarises the key conclusions from Hirabayashi *et al*. (2013) and Arnell and Lloyd-Hughes (2014) comparing RCP2.6 and RCP8.5. By 2050 there is little clear difference between the two extreme forcing scenarios, but the difference is more apparent by the end of the 21st century.

Study	Indicator	Year	RCP2.6	RCP8.5
Hirabayashi *et al*. (2013)	Average annual number of people (millions) flooded in ‘large’ floods; the 1971-2010 average is 5.6 ± 2.3. A ‘large’ flood is greater than the 1971-2010 100-year flood. No change in population. Range across 11 climate models.	2080s	23 ± 7	77 ±22
Arnell & Lloyd-Hughes (2014)	Percentage of global population living in major river floodplains, where the **frequency of flooding more than doubles**. Range across 21 climate models.	2050	1-5.6%	1-6.3%

Table 2.3.1 Impacts of climate change on global river flood risk: RCP2.6 compared with RCP8.5.

Figure 2.3.1 shows damage functions relating various indicators of change in global flood risk to change in global mean temperature. There is considerable uncertainty in the estimated impact for a given change in global mean temperature, and therefore uncertainty in the difference in impact between different temperature changes. The vast majority of the populations exposed to change in flood risk are in south and east Asia, so much of the uncertainty reflects uncertainty in changes in rainfall in these regions.

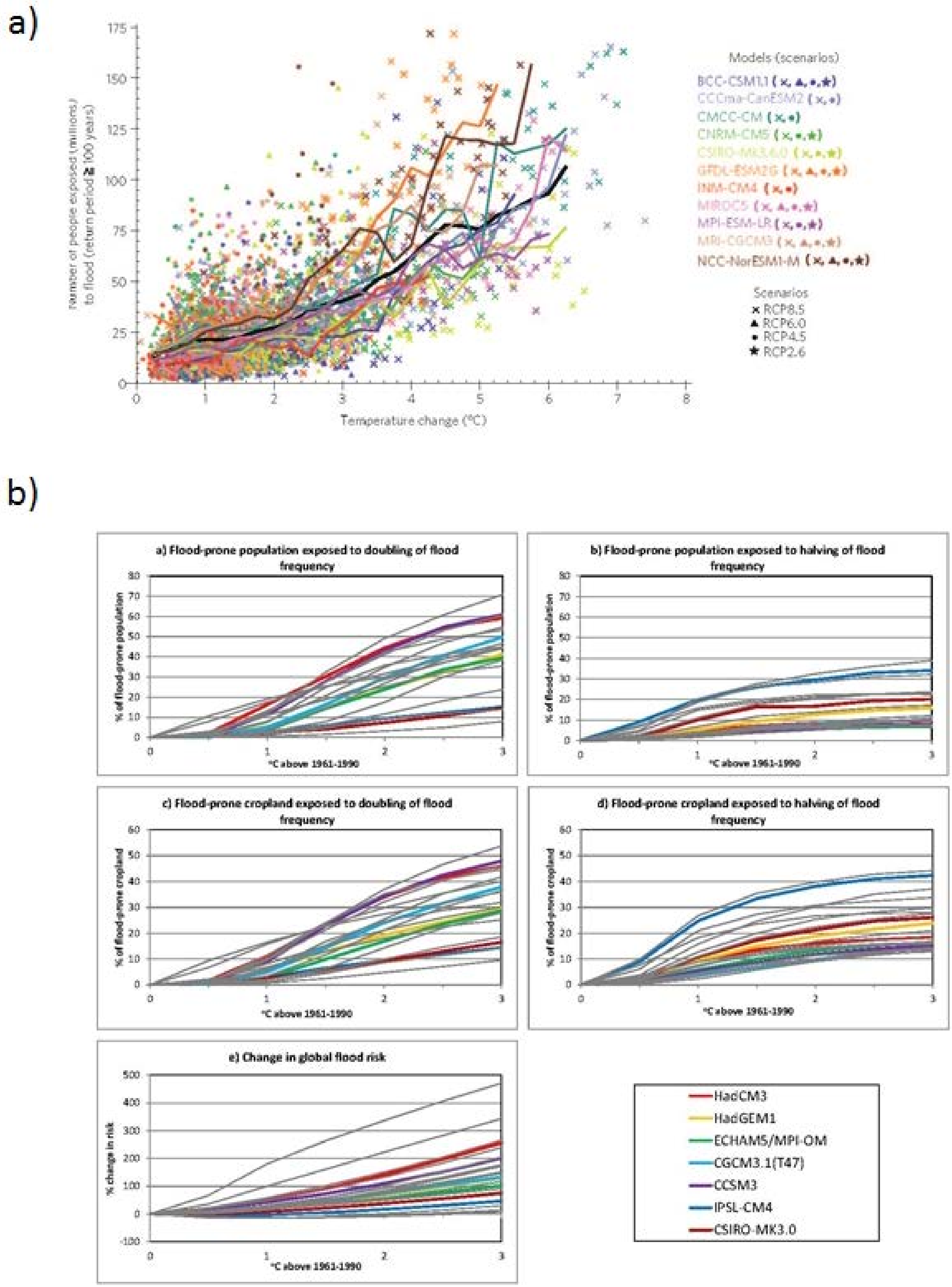

Figure 2.3.1. Damage functions showing change in indicators of global flood risk with change in global mean temperature. a) Hirabayashi et al. (2013): change relative to 1980-1999. b) Arnell & Gosling (2014): change relative to 1961-1990.

2.3.2 Extreme heat

Rather obviously, high temperature extremes become more frequent and low temperature extremes less frequent under RCP8.5 than RCP2.6, and this is well covered in AR5. More specifically, minimum temperatures generally increase more rapidly than maximum temperatures. Sillman *et al.* (2013) further show that under RCP2.6 maximum temperatures typically increase by less than 2°C (relative to 1981-2000) but minimum temperatures in northern high latitudes in winter may increase by more than 3°C. These increases are considerably smaller than those under RCP8.5; the median increase in maximum temperatures by 2081-2100 across all the CMIP5 models is approximately 6.5°C in some regions, and the median increase in minimum temperatures can be over 10°C.

Coumou & Robinson (2013) looked explicitly at extreme seasonal heat waves under the different RCPs with the CMIP5 models. They showed that even under RCP2.6 the area affected by extreme heat waves (more than three standard deviations (3-sigma) from the 1961-1990 mean) increases significantly, and in the tropics the 3-sigma event becomes the norm. They also presented a damage function showing the proportion of land area with summer temperatures more than one, two, three or four sigmas from the 1961-1990 mean (Figure 2.3.2).

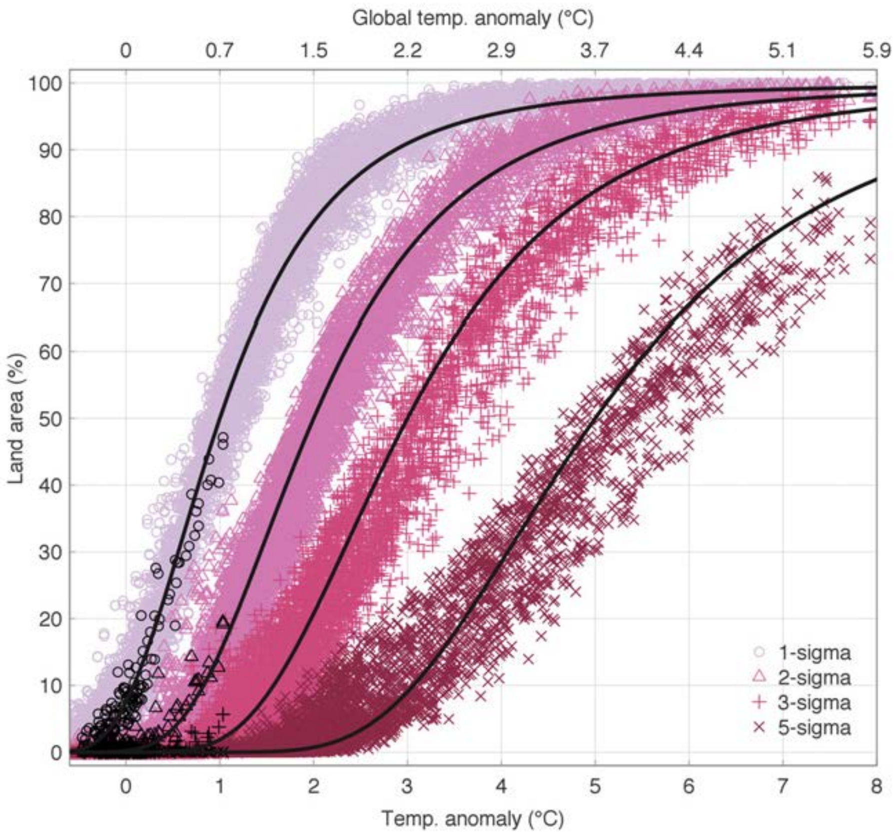

Figure 2.3.2. Damage function showing the proportion of land area with summer temperatures more than one, two, three or four sigmas from the 1961-1990 mean (Coumou & Robinson, 2013). The individual symbols represent individual model years. Global mean temperature change (relative to 1951-1980) is shown along the top horizontal axis; the bottom axis shows land temperature change.

2.4 Agriculture

Chapter 7 of AR5 (Porter, *et al*., 2014) provides an update on the state of knowledge since the Fourth Assessment Report, aggregating knowledge from some 2000 publications. However, this impressive collation and review of the literature, perhaps owing to page constraints, often lacks any real *synthesis*, but does aggregate large amounts of data into a series of figures and tables. Within the chapter, information on which models, baselines, and emission scenarios are used is not detailed, and the information provided largely comes from SRES emission scenarios and CMIP3 climate models. The key figures in the chapter summarize a large number of studies, referring to local temperature change but unfortunately often give little information as to how these were calculated, which models were involved nor which baselines. This is a significant source of uncertainty as the few baselines mentioned in the figure caption spanned a range of times from 1970-2005. Fortunately, some of this missing information is contained within a recent paper, written by many of the same authors (Challinor *et al.* 2014; see below).

Taking the above into account, the use of *local* temperature rise means that the impacts summarized below would occur at lower levels of global temperature rise as the land warms faster than the oceans, and higher latitudes faster than lower latitudes. Even measuring impacts at this level can contain uncertainties as small temperature rises in the tropics may be equivalent to larger temperature rises in temperate zones when considered relative to normal climate variability.

Key findings from AR5

i) The effects of climate change on crop production are already evident in several regions of the world with negative trends greater than positive ones.

ii)The greatest uncertainty in projecting crop yields is the extent to which increases in carbon dioxide will benefit yields (carbon fertilization). There are also uncertainties stemming from variation from scale of experimental studies, interactions with ozone and nitrogen, and interactions with climate (temperature and precipitation). It should be noted that many of the crops expected to show enhanced yields with carbon fertilization are showing negative yield trends associated with climate change in tropical regions, but positive trends in high latitude temperate areas. .

iii) Carbon fertilization and climate change will potentially lead to range increases and greater competitiveness of invasive weeds.

iv) In the absence of adaptation even small local temperature increases (~1°C above pre-industrial) will negatively affect yields for major crops over wide areas.

Therefore negative impacts on yields, without adaptation, would be expected to continue and increase with median yield impacts of 0 to -2% per decade from the 2030s. Models examining yield projections in the absence of carbon fertilization estimate global food price increases ranging from 3-84%.

Key findings post-AR5

Several model intercomparison (Agricultural Model Intercomparison Project, AgMIP) and meta-analyses have been published, either as a more in-depth review of the same material in AR5 or since the cut-off for inclusion of literature in the AR5. These papers provide a greater level of detail as to model suitability and uncertainties to consider in the AVOID project.

The most significant of these papers was a large meta-analysis performed by Challinor *et al.* (2014) which examined 1700 published simulations estimating yield impacts of climate change and adaptation. This paper builds on, and provides more information than space constraints allowed, the material in AR5. As is usual in many meta-analyses there is no explicit listing of the range of climate models, crop models, or assumptions used. However, the paper did find an overall loss in yield for wheat, rice and maize for both temperate and tropical regions by 2°C of local warming (global temperature rise of less than 2°C) if there were NO adaptation. However, they found that adaptation can offset these losses, at least in temperate regions. Challinor *et al.* (2014), and the AR5 (IPCC 2014a) separated adaptation into a series of categories: incremental changes of existing systems (cultivar, planting times, irrigation); systemic changes (crop species or grazing integration); and transformational changes (crop relocation, changes in farming systems).

One significant issue these authors found (and this is equally true with biodiversity and ecosystem studies) was a lack of model documentation as well as any standardization of model experiments. In contrast to agriculture findings in AR4, this meta-analysis found robust yield reductions for all major crops, especially after 2°C of local warming. Adaptation benefits were also found to differ by crop with clear benefits for wheat and rice but not maize. With adaptation, wheat yield losses might be avoided for up to 2-3°C of local warming in tropical regions. However, few of these studies factor in extreme heat or other extreme events. However, these adaptation results substantially differ from those found by Moore and Lobell (2014). In their analysis of potential adaptation options in Europe, Moore and Lobell found that adaptation had clear potential benefits for maize, but not for wheat or barley with 2°C of warming.

The recent research on the potential impacts of climate change on agriculture show that there can potentially be large differences between regional and global studies, especially if there have been an aggregation of results. In part, this may be due to differences in how adaptation is examined. Challinor *et al.* (2014) looked at potential adaptation practices while Moore and Lobell (2014) based there analysis of adaptation potential on the reaction to European farmers to climate variability, building their projections on this. The more empirical approach of Moore and Lobell (2014) also found that there is currently a decline in agriculture profitability of 9.7% in years that are 1 standard deviation warmer or cooler during the growing season. Finally, Wing and De Cian (2014) have reviewed forthcoming work by Hertel and Lobell who have found that there is a risk of overstating the potential benefits of adaptation in agriculture, especially in poorer countries. This work is largely based on the potential costs of planned adaptation where there technological changes will be required.

One of the advantages of this meta-analytical approach was the ability to develop a general yield formula. Combining all of the published data allowed the authors to broadly estimate yield losses of 4.9% per °C. Precipitation and CO_2 increases can offset some of the losses: 0.53% yield increase per % precipitation change, and .06% increase per ppm change in CO_2. The overall benefit of adaptation was calculated to be a 7.16% higher yield than with no adaptation

A second meta-analysis looked at human health/nutrition (Myers *et al*., 2014). While many agriculture papers discuss a potential carbon fertilization effect, there is far less mention of the other side – a reduction in protein levels in the edible portions of the plant. This meta-analysis looked not only at protein but also changes in levels of iron and zinc. This study examined 143 comparisons of the edible portion of crops from seven different FACE (free air concentration experiment) studies looking at 18 varieties of rice, 8 of wheat, 2 of maize, 7 of soybeans, 5 of field peas and 1 of sorghum.

Currently, 2.3 billion people live in countries whose populations receive at least 60% of their zinc or iron from C_3 grains or legumes, with 1.9 billion receiving at least 70% from these sources. Therefore, reductions in zinc and/or iron would add to the burden of disease in these countries. This study found significant decreases in the concentrations of zinc and iron in all C_3 grasses and legumes. This is significant as an estimated two billion people are currently suffering from deficiencies in these minerals, leading to a reported loss of 63-million life-years annually. Protein levels were noted to be significantly lower in wheat, rice and field peas. Ranges and values are given for both minerals, and protein for all crops examined. Of the crops examined, only rice showed a difference between varieties for iron and/or zinc reductions.

Of the model intercomparison studies done, only the AgMIP project (Rosenzweig *et al*., 2014) looked at RCP scenarios and CMIP5 climate change models. However, while this project looked at all four of the RCP scenarios, it only examined five GCMs (General Circulation Models). This may be an issue owing to broad differences between model sensitivity to differing forcings; issues potentially exacerbated when looking at different regions owing to potential differences in sign in precipitation changes. The precipitation differences may not be as much of an issue as the temperature impact on yields is approximately 5-10 times greater than that of precipitation.

The AgMIP team examined seven different agricultural models from three broad classes. Overall, the team estimated that the yield uncertainty from the agricultural models used was greater than from the climate models for a given emission scenario. However, this assumes that a) all models have an equivalent chance of being correct and b) that the models are not sensitive to regional precipitation sensitivity differences in the climate models. One approach to better understand agricultural model uncertainty would be to try and examine the differences in model yields when equivalent parameters of the models were turned on and off – thus, models being run using similar inputs (e.g., no CO_2 fertilization, no adaptation, no fertilizer use, etc.). Nevertheless, the paper does point out key areas where uncertainty needs to be better understand – carbon fertilization, nitrogen stress, and high temperature effects.

A key point in many of these studies is that they look at a narrow range of crops. While these crops may make up the majority of the crops consumed globally, there are large local differences and many other crops that humans can, or could, consume. Far more analyses is needed on potential yield changes in alternative crops to potentially better understand regional impacts of climate change on agriculture.

There is also new work on potential impacts of agricultural land use on regional climates that potentially needs to be incorporated into agricultural models. China has been shifting from single cropping (SC) to double cropping (DC) in the North China Plain (NCP, a region of 10° latitude by 10° of longitude) in order to deal with increasing food demands. These changes have been found to have regional climatic implications (Jeong *et al*. 2014). In the NCP, those areas under DC average 0.7°C warmer in the inter-cropping season (June and July) than those in SC. Most of this change was in T_{max} where the temperature increase was 1°C. This difference was found to largely be due to reduced transpiration in the DC area (as the soil was bare or there was limited stubble). This temperature change is occurring during the peak of the East Asian monsoon and the differential warming owing to land use change was found to have regional impacts on precipitation with decreases in parts of Korea and increases in parts of Japan. As these areas depend on rain fed agriculture then changes in agricultural practices in one region are having impacts in other. Jeong *et al.* (2014) identify this as a potential area for improvement in agricultural models.

2.5 Biodiversity and ecosystems

There are many different ways of modelling the potential impacts of climate change on biodiversity at the species level. These include species distribution models (SDMs, also called climate envelopes), species specific population dynamic models (PDMs), species specific trait analyses, and potential paleoecological proxies. At the level of entire ecosystem there are techniques that are largely based on either analyses of what may occur to an entire biome or vegetation class (especially as the definition of these are often based on climate alone or climate + soil), or on ecosystem functioning (usually represented through General Vegetation Models (GVMs). All of these techniques can yield meaningful results when used primarily for the purpose they were originally designed for (e.g., GVMs for net primary productivity, SDMs and PDMs for individual species.

There have been significant advances in modelling the potential impacts of climate change on biodiversity, especially on individual species, in the last five years and the field is on the cusp of major advances over the next five years, especially as different techniques are combined. Some of the best work has come in the fields in species specific population dynamic models, yet the complexity of these models (often calculated for only a portion of a species overall population) limits their usefulness at looking at broad global analyses. These PDMs might be viewed more like yield in agriculture. Species based trait analyses are just now coming into more widespread use with the availability of large databases. These traits based analyses have been used in both species level modeling and in GVMs to improve their estimates of adaptation potential and potential impacts of climate change.

One of the key statements in AR4 was that “Approximately 20 to 30% of plant and animal species assessed so far (in an unbiased sample) are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3°C above pre-industrial levels.” These numbers were developed during the SPM Plenary in cooperation with Governments but based on the literature review contained in the chapter and subsequently published as a more complete meta-analysis (Warren *et al*. 2011). Many of the subsequent issues that have arisen around this statement have come about because of a lack of definition as to what “increasingly high risk of extinction” means. The text of AR4 did not mean that 20% to 30% would go extinct, just that the vulnerability increases the risk with rising temperature. These figures came from a broad range of studies, using a range of models and assumptions but normalized to a standard set of temperatures. Since the AR4 there have been many papers on climate change and biodiversity or ecosystems, using a greater range of methods, models, dispersal and adaptation assumptions. These range from demography studies (usually most suitable for a single species in a single region), to traits-based analysis, to bioclimatic models using multiple techniques. No equivalent meta-analysis of the papers looking at potential extinctions risks (as above) in individual or small groups of species was performed for the 5AR. However, two major papers looking at large numbers of individual species came out too late in the AR5 process to be fully considered. One, used a traits-based analysis (Foden *et al*. 2013) and looked at almost 17,000 species and one a bioclimatic modelling approach (Warren *et al*.

2013) that looked at almost 50,000 species. There are fundamental, and critical, differences between these two studies that underscore the potential robustness of the findings and how these findings might relate to the 20-30% figure used in the AR4.

Foden, *et al.* (2013) did not use any direct species bioclimatic modelling to assess species' vulnerability, looking instead at traits that might make them more, or less vulnerable, to climate change. This is a major difference with both the studies in the AR4 and Warren *et al.* (2013). They also looked at potential intrinsic adaptation, the first time this has been directly included. Having assessed the traits of these species and their potential sensitivity to various climate parameters they then looked at 4 GCMS (CMIP3) and two time periods essentially averaging to be at approximately 2°C and 3°C. With 2°C warming and optimistic adaptation 24-50% of the World's birds, 22-44% of the World's amphibians, and 15-32% of the World's corals were found to be highly climatically vulnerable. Thus, these numbers, especially for terrestrial species, are similar to those developed in AR4, but arrived at using an entirely different methodology and including adaptation.

Warren, *et al.* (2013) used direct bioclimatic modelling, with new methods for assessing dispersal potential on a far greater number of species than had previously been examined. One of the key points of the Warren paper is the inclusion of a great many widespread species, species generally not thought to be as sensitive to climate change. Of the ~50,000 species examined, 57±6% of plants and 34±7% of animals were found to be likely to lose ≥50% of their present climatic range by the 2080s under a realistic dispersal scenario. For comparison, this would be with a temperature increase of approximately 3.5°C considered across the 7 GCMs in the study. These percentages were tested with subsets of the taxa data and found to be generally robust. This study differed from most previous studies in explicitly looking at mitigation options using the scenarios developed for the AVOID I project. They found that the potential range losses (and thus the vulnerability) are reduced by 60% if emissions peak in 2016 and 40% if emissions peak in 2030. These reductions allow decades of additional time for adaptation.

There are still many advances that can be made to reduce the uncertainties in these sorts of assessments. One that is ongoing is an attempt to merge the approaches of Foden (*et al*. 2013) and Warren (*et al*. 2013) such that the bioclimate models are used to assess exposure and the traits are used to assess vulnerability and adaptation potential (McDougall 2014). Other improvements would come from using more modelling techniques, looking at extreme climatic events, improving assessment of dispersal and by using updated climate models and newly developed uncertainty minimization techniques.

Ecosystem level changes can be examined using SDMs (as above) for species composition (sometimes considered bottom-up), and GVMs for ecosystem functioning (sometimes considered top down). Previously, GVMs have also been used to infer biodiversity changes (especially pre-AR3). Limitations of using this technique for this purpose have been covered in both the AR3 and AR4. The key limitation in this use is that the main component of a GVM is a plant functional type (PFT). This PFT can be viewed as a conglomeration of many of the species that might potentially be found in a given area. Thus, depending on the GVM, the PFT is one to two steps removed from actual species. For ecosystem functioning, especially for net primary productivity, but also in carbon modelling, this may be the best that can be done as the data for individual species may be incomplete. The GVM approach is currently used in many land use change models (e.g., Arneth *et al*. 2014). There is also an analogous CFT or crop functional type, used in some GVMs, for agricultural land. There are a number of key limitations to using GVMs for ecosystem change, especially at the species/biodiversity level – there is a large body of paleoecological evidence that species responded to paleoclimatic changes as individuals, not groups, and that there were assemblages in the past that have no analogue to the present; many plants are long-lived (centuries) and while they may stop reproducing the species will still be present in the absence of disturbance; different plants have different dispersal capabilities and distances.

The ISIMIP program has performed a model intercomparison (Warszawski *et al.* 2013) on GVMs to examine how a top-down approach could assess ecosystem functioning. While a significant first step it important to bear in mind that the current ISIMIP comparison only examined a small number of the global vegetation models available. Nevertheless, the numbers they came up with do not differ significantly from estimates from similar, previously published studies (Warren *et al.* 2010). The ISI-MIP GVM ecosystem results found that 28% (20%-38%) of the natural vegetation is at risk of severe ecosystem risk with a temperature increase of 2° to 3°C. Thus depending on the choice of definition of severe ecosystem risk, increasing risk of extinction, or increasing risk of climate variability to overall estimate of % at risk is approximately the same (range is slightly larger) as that reported in the AR4 looking at far more species and using many different techniques.

It should be noted, however, that while the global numbers may be similar, there are substantial differences in regions that may be most at risk. This is true not only among the different GVMs in ISI-MIP (Warszawski *et al.* 2013), but also in comparison with results from aggregating across large numbers of individual species models (Warren *et al.* 2013), generally agreeing for the Amazon and parts of the Arctic.

All of the techniques discussed under biodiversity would potentially benefit from better merging of the different techniques. For example, the incorporation of species traits, extreme events, interactions and the development of techniques to better assess the relative contribution of different components of top down (GVM) and bottom up (SDM) approaches – merging components of models where possible.

2.6 Coastal Flood Risk

(i) Projections for sea-level rise range (based on the 5% and 95% levels) from 0.26m to 0.98m for RCP 2.6 through to RCP 8.5 in 2081-2100, with respect to 1986-2005. Semi-empirical models of sea-level rise suggest rates potentially 'twice as large as the process based models', but these projections are given low confidence (Church *et al*. 2013). However, in terms of impacts, this upper range is considered as the worst case scenario needs to be planned for, however unlikely (Wong *et al*. 2014).

Given the potentially large range of rise, coastal impacts are highly uncertain, particularly as adaptation can greatly reduce the adverse consequences of rise. Regardless of the rate of rise, there is very high confidence that submergence, flooding and erosion will occur, and high confidence that this will happen at an increased rate, thus increasing the risk of exposure of population and assets to extremes as shown through local to global scale case studies in AR5. The most vulnerable areas include south, east and south-east Asia, Africa and small islands due to financial ability, remoteness and ability to adapt. Coasts are in multi-stressor environments as sea-level rise may not be the most important factor driving change. In susceptible large cities (usually those built on deltas), land subsidence can be one or two orders of magnitude larger than sea-level rise. Socio-economic factors such as population growth, coastward migration and economic growth (e.g. tourism) are also important, but their inter-relationship with climate change is less explored. Adaptation as a means to increased climate resilience and create more sustainable coastlines has advanced more in developed countries than developing. For the latter, adaptation derives greatest benefit where it goes hand-in-hand with wider development.

Wong *et al*. (2014) mostly used outputs from process based models using the SRES scenarios. SRES scenarios relating impacts to forcing are also reported in Arnell *et al*. (2014) and Brown *et al*. (2013) at global and regional scales. No impact studies involving RCP scenarios were reported, but since then Hinkel *et al*. (2014) has reviewed and analysed flood damage and adaptation costs.

(ii) Selected examples of quantitative outputs of impacts, assuming no further adaptation takes place. Many regional and more local values and articles are also available (but not referenced due to space). Details for all in papers or supplementary material. City/port studies also available, including population and costs (Hanson *et al*. 2011; Hallegatte *et al*., 2013).

Reference	**Climate scenario**	**Socio-economic scenario**	**Temp (wrt pre-indust) / SLR (wrt 1961-1990)**	**Output metric, assuming no upgrades in adaptation**
Nicholls *et al*. 2011	n/a	A1B	0.5-2.0m (in 2100)	72-187 million people displaced
				0.88–1.8 million km^2 of dryland loss
Brown *et al*. 2013	A1B	A1B	2.6-4.0°C, 0.29-0.53m (in 2090s, range taken over 9 models)	243-311 thousand km^2 net wetland loss
				0.45-0.71 million km^2 dryland loss
				62-134 million expected number of people flooded per year

Hinkel *et al*. 2013	Mitigation 450ppm, semi-empirical	Between SRES B1 / B2	0.4-1.3m (in 2100)	117-262 million people annually flooded
Arnell *et al*. 2014	A1B	A1	3.3°C and > 0.27m in 2050	20%-28% decrease in wetland extent 25 to > 200 million average annual number of people flooded
Hinkel *et al*. 2014	RCP2.6, 4.5, 8.5	SSP1-5	0.25-1.23m in 2100	0.2-4.6% population expected to be flooded annually 0.3-9.3% expected losses in GDP US$12-71 billion annual investment and maintenance costs of dikes

(iii) Few inter-comparison studies have been undertaken as modelling capacity and expertise at global and regional levels is limited. Within the main model used for these projections (DIVA), the main uncertainty is the magnitude of ice melt. Hinkel *et al*. (2014) includes uncertainty into different global gridded elevation and population data.

(iv) There is increasing recognition that social factors are important (e.g. population exposed to a 1-in-100 year coastal flood is expected to increase from 270 million to 350 million in 2050 for socio-economic reasons alone, Jongman *et al*. 2012), but these require better integration into impacts projections. Modelling global and country scale impacts does not allow for detailed changes that may be unique to the coast (e.g. migration, increased economic growth). Social issues, such as development and the means to adapt are included in global projections, but are limited as the types and effectiveness of adaptation that is able to be modelled. The long-term effectiveness of newer forms of artificial defence (e.g. man-made dunes) are unknown. Further work is required to integrate all social factors, with adaptation options and adaptive capacity worthy of further explanation.

2.7 Energy demand

Only one global study of the potential effects of climate change on energy demand was cited in AR5 Chapter 10 (Arent *et al*, 2014). That study (Isaac & van Vuuren, 2009) compares regional and global residential heating and cooling energy demands under unmitigated emissions and a pathway that achieves the 2^{o}C target; it estimated (under just one climate model pattern) that at the global scale total residential heating and cooling demand would decrease to around 2050, then increase as cooling demands increased more substantially than heating demands reduced. Under unmitigated emissions total demand would increase above current levels by 2070, but under the policy scenario total demand would remain below current levels. However, there is substantial variation between regions.

A simplified version of the Isaac & van Vuuren model was used in AVOID to estimate residential energy demand (Arnell *et al*., 2013), and used in Arnell *et al*. (2014) to produce damage functions for change in residential heating and cooling demands. Figure 2.7 shows the functions relating change in global residential heating and cooling energy demands with increases in temperature above the 1961-1990 mean. The different lines represent different climate model patterns. For example, with a 2°C rise in temperature (relative to 1961-1990), global heating energy demand in 2050 would be 20 to 27% lower than in 2050 with no climate change, and global cooling energy demand would be 40 to 60% higher than in the absence of climate change.

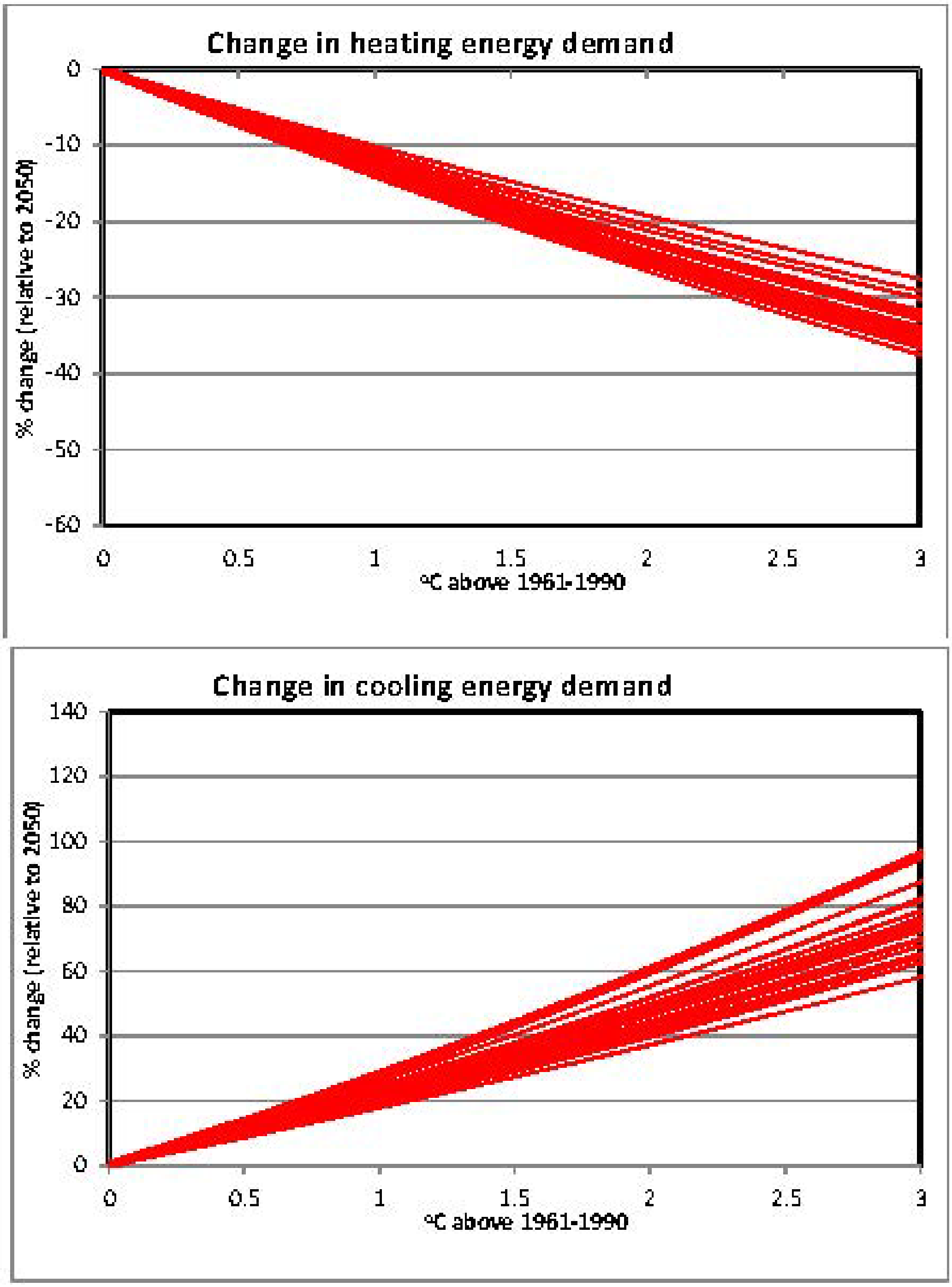

Figure 2.7. Damage function showing change in residential heating and cooling demand in 2050 with global mean temperature change (relative to 1961-1990). The different lines represent different climate model patterns. Arnell et al. (2014).

2.8 Human health

Effects of climate on human health are fundamentally linked to most of the other "sectors" included in this review. There are *direct effects*, as in heat related morbidity or injuries due to extreme weather, or *indirect effects via reduced food or water access or via changing disease vector distributions*, or *indirect effects via social upheaval*, such as migration due to river flooding or sea-level rise (Bowles *et al*., 2013). The impacts of climate change (CC) on population health are very much determined by the background health status of the local population, and the AR5 highlights that many of the CC related health risks are exacerbation of current health problems (IPCC 2014). This means that low income populations with poor health status are at particular risk. Available estimates of regional or global human health impacts of CC have incorporated aspects of the "three types of study" to take socio-economic future into account, but the use of "likely average scenarios" obscures the much greater negative health and other impacts on the most disadvantaged parts of populations (IPCC 2014).

The AR5 concluded (IPCC 2014) that with high or very high confidence there will be a greater risk of injury, disease and death due to periods of more intensive heat or fires, increased risk of under-nutrition resulting from diminished food production, increased risk of food- and water-borne diseases, and negative consequences for health of lost work capacity and reduced labour productivity in vulnerable populations. New studies are published every month, and they confirm the AR5 conclusions and add more detail useful for quantifications of health and social impacts. This short review will focus on increasing heat stress, reducing cold stress and the links to labour productivity and economic impacts, which has been estimated to be the most costly aspect of CC impacts on local populations (Kjellstrom *et al*., 2009; DARA, 2012).

It is important to consider that community health and well-being impacts of climate conditions depend on the immediate local conditions, and global average estimates of temperature or humidity change will not be good indicators of future exposures. Mapping exposures using relatively fine grid cells (0.5 by 0.5 degrees) create a better basis for risk analysis (e.g. Hyatt *et al*., 2010; Kjellstrom *et al*., 2013). A number of studies have analyzed the Urban Heat Island effect, which creates higher heat exposures (several degrees C) in urban areas than rural surroundings (Oke, 1973). An analysis for a large number of US cities (Stone, 2007) showed that the time trends of increasing heat were also faster in the urban areas.

The first quantitative global estimate of additional deaths due to climate change (scenario A1B) from 1990 to 2000 concluded that it could be 166,000 (McMichael *et al*., 2004). An update of the number of deaths from 2000 to 2050 (Scenario A1B, WHO, 2014, in press) estimates that maybe another 350,000 deaths will occur in under-nutrition, malaria, dengue, diarrheal diseases, heat exposure at work and in homes, and the effects of economic changes. The morbidity changes have not been quantified in a similar manner, but it is likely to be much bigger. As an example, the physiological stress caused by excessive heat in workplaces will reduce available work hours for billions of people (Kjellstrom *et al*., 2014, in press), and the equivalent "burden if disease" impact is much greater than the estimated deaths and clinical morbidity impacts. The only available quantification of the related economic impacts (Scenario A1B, DARA, 2012) showed that "labour productivity loss due to increasing workplace heat exposures" was by far the greatest economic threat from climate change. Already in 2030 the cost of lost productivity due to workplace heat was estimated at 2,400 billion USD PPP. Analysis with RCPs and new models is not available yet.

The main uncertainties in modeling emerge from each modeling step where the climate conditions have to be estimated for local areas where the local population is exposed to the climate. Then there is uncertainty in how the different health impact models represent the actual impacts, particularly for the indirect effects (WHO, 2014 in press). The variability of climate vulnerability within the local populations is another uncertainty factor, and this depends on access to health services as well as any preventive policies and programs implemented by the local health sector. Different estimates will also develop depending on the type of heat exposure index that is used (Parsons, 2014). Temperature in itself is not representing the actual physiological heat stress, as humidity, wind speed and radiated heat contribute to heat and cold exposure. For workplace exposures the Wet Bulb Globe Temperature (WBGT) is the most commonly used index (Parsons, 2014), and modern computer programs make it easy to present heat and cold exposures in the form of any index based on the raw input climate data.

The main social issues left out of the modeling of health and other impacts to date include the effects of climate conditions on labour productivity. If this indeed is the costliest of the different effects of climate change on human communities in large parts of the world, it needs to be analyzed in more detail and given more visibility in national assessments (the recent US assessment almost totally ignores this issue). Another social issue that has not been quantified sufficiently is the inequitable distribution of impacts within populations. There are also new health concerns with important social links but with very limited ongoing research. This includes the social impacts of excessive outdoor heat conditions limiting possibilities for continued social activities in communities, and it includes the risk of heat exposures in special groups, such as pregnant women.

This can all be analyzed in the context of economic impacts, but specific research on the economic links to different health impacts is rare. The main analysis, such as the Stern report and follow-up work by Stern and others, has focused on using macro-economic analysis methods to link different sectoral developments to the economy. However, the role of human input into raw materials extraction, agricultural production, manufacturing, construction, and intellectual work has not been analyzed in the context of the heat exposure impacts on human physiology and psychology (Parsons, 2014). The only analysis that has brought in the productivity impacts in a global setting is the Climate Vulnerability Monitor 2012 (DARA, 2012) which used work capacity loss analysis in 21 global regions as its starting point (Kjellstrom *et al*., 2009a). The losses of work capacity were multiplied with the GDP estimates for different countries and very high impacts were reported. For instance, in 2030 India and China would each loose 450 billion USD per year due to increasing heat in workplaces, and in the USA the economic loss for this reason would be 150 billion USD (DARA, 2012).

This report has been curiously ignored by all other global climate change impact assessments, and the most recent assessment for the USA (Kopp *et al*., 2014) is for the only other assessment that makes Labour Productivity a key climate change economics issue. However, the heat effect was based on time use studies (Graff, Zivin and Neidell, 2014) that showed that high vulnerability work was affected by heat in the sense that people worked less ours on very hot days in the USA. The underlying physiological mechanisms were not mentioned at all. The Australian Garnaut report and the World Bank reports also overlook this issue, which was first raised by Kjellstrom *et al.* in 2009b.

The IPCC health impact assessment in 2014 gave this issue visibility, but the economic costs were not further analyzed. In the IPCC economic impact chapter an analysis by Dunne *et al.* (2013) was referred to. This analysis used similar approaches as Kjellstrom *et al.* (2009a) and it was stated that as much as 20% of global labour productivity may be lost due to heat this century. There is a great need for further improved analysis of this issue, and for renewed estimates at country level, so that the implications for local socio-economic development of the ongoing climate change become clearer. The analysis should also look at the different mitigation and adaptation options and attempt to make economic estimates of the various choices.

A key issue in economic interpretation will be the discount rates for preventive costs now and economic gains in the future. By expressing the economic challenges in terms of future labour productivity, it may be possible to get agreement on the extent to which discounting makes sense when health impacts are estimated and interpreted.

2.9 Conflict and security

Chapter 12 of AR5 WG2 (Adger *et al*., 2014) summarises available evidence on the implications of climate change for conflict and security. The chapter, however, is very qualitative and conceptual – reflecting the nature of the evidence. The key conclusions are:

- Human security will be progressively threatened as climate changes
- Climate change will have significant impacts on forms of migration that compromise human security (but many vulnerable groups do not have the resources to be able to migrate and migrants may themselves be vulnerable to climate change impacts)
- Some of the factors that increase the risk of violent conflict within states are sensitive to climate change
- People living in places affected by violent conflict are particularly vulnerable to climate change.

A number of papers (e.g. Burke *et al*., 2009; Hsiang *et al*., 2013) have sought to produce quantitative evidence on the link between climate and conflict, and used models to estimate future impacts, but these are very controversial. Quantitative results have been shown to be very sensitive to model form, data coverage and also the conceptual framework used (Buhaug, 2010; O'Loughlin *et al*., 2014), and claims of detection and attribution of quantitative links between climate change and past conflict are therefore premature.

However, there is some evidence that climate variability (as opposed to change) is associated with conflict (IPCC AR5 gives this a medium confidence level), and because drivers of conflict *are* sensitive to climate change, IPCC AR5 notes that this could become a key risk in the future.

2.10 Economic growth and aggregate impacts

Assessments of economy-wide consequences of climate change report results either as total damages or as marginal damages, the latter represented by the social cost of carbon (SCC). Estimates of aggregated impacts differ significantly between models and across sectors, regions, countries and populations (Ackerman & Stanton, 2013; Anthoff and Tol, 2010; Bosello *et al*., 2012; Hope, 2013a, 2013b; Nordhaus, 2008, 2010; Roson and Mensbrugghe, 2012). Aggregate damages are influenced by development pathways, but this relationship is not well explored. In some locations and amongst some groups of people with high exposure and high vulnerability, net costs per capita will be significantly larger than the global average (Anthoff *et al.*, 2009; Nordhaus, 2011; Warren, 2011; Ciscar *et al*., 2011; Hauser *et al*., 2014). Damages as a fraction of output are expected to be larger in low-income economies, but monetized damages are expected to be larger in high-income economies (e.g., Anthoff and Tol, 2010).

The IPCC AR5 (SPM, Chapters 10 and 19) presents recent estimates of the total global aggregate impact of climate change, indicating that global economic losses with an increase in global mean temperature of 2^{o}C (above pre-industrial) would be between 0.2 and 2.0% of GDP. Chapter 10 (Arent *et al*., 2014) presents a plot summarising estimates of global aggregate impact as a function of change in global mean temperature. However, Ch. 10 and the plot are still being corrected at the time of writing as a result of errors found in the literature as described below. Although there are few studies for additional warming around 3°C or above, IPCC AR5 SPM concludes that there is a robust finding that aggregate economic damages accelerate with increasing temperature.

The social cost of carbon (SCC) is an index of marginal aggregate damages that monetizes the expected welfare impacts, in a given year, of a small increase in carbon dioxide emissions (i.e., the welfare loss associated with an additional tonne of CO_2 emitted) (Newbold *et al.*, 2010; Nordhaus, 2011a; Tol, 2011; Kopp and Mignone, 2012). Numerical estimates of the SCC published span a large range. Peer-reviewed estimates (as compiled by Tol, 2011, 2013, with the addition of estimates from Kopp *et al.* 2012) range from -\$2 to \$1000/tonne CO_2, with most estimates between \$4 and \$50/tonne CO_2 (in inflation-adjusted 2010 dollars, for CO_2 emissions occurring in the first fifteen years of the twenty-first century).

The IPCC AR5 WG2 SPM cautions that estimates of aggregate impacts are very uncertain, because they vary in their coverage of sectors and their accounting for catastrophic change and tipping points, and because they are dependent upon a number of questionable assumptions. Since approval of the WG2 SPM, estimates have been further questioned, and have been highly controversial. Tol (2009)'s literature review (which underpins the IPCC WG2 Chapter 10 plot) has been corrected following the identification of a number of errors, and this too has been criticised (but not in peer reviewed literature) for its strong reliance on assumptions about the shape of relationship between temperature change and aggregate impact.

Systematic uncertainty in estimates of global aggregate impacts arises because most cost-benefit type integrated assessment models exclude a number of potentially significant factors (Yohe, 2008; Füssel, 2010; Kopp *et al.*, 2012; Revesez *et al*. 2014), including the consequences of earth system tipping points (Kopp and Mignone, 2012; Lenton and Ciscar, 2013), intersectoral and interregional interactions (Bosello *et al.*, 2012; Warren, 2011) including the potential for climate-change inducted migration and conflict, and the imperfect substitutability of environmental goods, which reflects the fact that impacts on (for example) ecosystems cannot be replaced 1-for-1 by an increased consumption of material goods (Kopp *et al.*, 2012; Weitzman, 2010). Models do not include the effects of the degradation of ecosystem services by climate, such as the consequences of the loss of biodiversity (as a source of pollination agents and wild crop types) for agriculture. Additionally, studies lack evidence for extrapolating damages from temperature increases at which impact studies have been carried out to higher temperatures (Ackerman and Stanton, 2012; Kopp *et al.*, 2012; Weitzman, 2010). Aggregate damage estimates are also affected (with unclear sign) by the treatment of adaptation therein, which is inconsistent across studies (Bosello *et al.*, 2010; de Bruin *et al.*, 2009; Füssel, 2010; Hope, 2006; Patt *et al.*, 2010).

Two factors generally excluded from aggregate impacts are labour productivity losses and impacts due to climate variability (such as the response of human health and crops to extreme heat) (Revesez *et al.* 2014). These two factors were included in the recent ‘Risky Business’ report (Bloomberg *et al*, 2014) and its underlying ‘American Climate Prospectus’ technical report (Houser *et al*., 2014), which were based on a bottom-up regionally- and sectorally-specific assessment of climate change damages in the USA. This study found that, in the absence of emissions reductions and/or faster-than-historical adaptation, many regions of the US risk ‘serious economic effects from climate change’ over the 21st century. These risks include increases in heat-related mortality, reductions in outdoor labour productivity, loss of coastal property and infrastructure, and increased energy demand.

3. Overall conclusions

It is clear that there is still a need for the next deliverable of this project (AVOID2 WPB deliverable 1b), where we will produce a ‘meta-analysis’ of papers – summing totals by scenario (RCP etc), scale, sector and (e.g.) socio-economic assumptions (e.g. SRES or SSPs) – to synthesise existing studies together. However, this literature review has identified that in some cases (e.g. agriculture) the number of publications is very large, hence a full meta-analysis will not be possible within the scope of the project.

New model inter-comparison work is producing very interesting results, but this work is rather in its infancy and much remains to be done to tease out the reasons for differences between impacts projections. It is clear from these studies, however, that it is key to use multiple impacts models to characterise uncertainty in several sectors, such as water security and agriculture.

Whilst some policy messages, such as the proportion of impacts avoided by mitigation efforts, are likely to remain robust in spite of these uncertainties, the implication of the model inter-comparison studies is that more work is need to understand intermodal differences and increase our confidence in the precise levels of climate change impacts projected under specific future climate scenarios.

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Appendix

Table 2.1: Effects of different GHG emissions scenarios on changes and freshwater-related impacts of climate change on humans and ecosystems (Jimenez *et al*., 2014 Table 3.2). Among the SRES scenarios, GHG emissions are highest in A1f and A2, lower in A1 and B2, and lowest in B1. RCP8.5 is similar to A2, while the lower emissions scenarios RCP6.0 and RCP4.5 are similar to B1. RCP2.6 is a very low emissions scenario (Figure 1-4 and Section 1.1.3.1 in Chapter 1). The studies in the table give global warming (GW: global mean temperature rise, quantified as the CMIP5 model mean) over different reference periods, typically since pre-industrial. GW is projected to be, for RCP8.5, approximately 2°C in the 2040s and 4°C in the 2080s. For RCP6.0, GW is 2°C in the 2060s and 2.5°C in the 2080s, while in RCP2.6, GW stays below 1.8°C throughout the 21st century (Figure 1-4 in Chapter 1). Population scenario SSP2 assumes a medium population increase.

Type of hydrological change or impact	Description of indicator	Hydrological change or impact in different emissions scenarios or for different degrees of global warming (GW)	Referenc e
Decrease of renewable water resources, global scale	Percent of global population affected by a water resource decrease of more than 20% as compared to the 1990s (mean of 5 GCMs and 11 global hydrological models, population scenario SSP2)	Up to 2°C above the 1990s (GW 2.7°C) each degree of GW affects an additional 7%	Schewe *et al.* (2013)
Decrease of renewable groundwater resources, global scale	Percent of global population affected by a groundwater resource decrease of more than 10% by the 2080s as compared to the 1980s (mean and range of 5 GCMs, population scenario SSP2)	RCP2.6: 24% (11-39%) RCP4.5: 26% (23-32%) RCP6.0: 32% (18-45%) RCP8.5: 38% (27-50%)	Portmann *et al.* (2013)
Exposure to floods, global scale	Percent of global population annually exposed, in the 2080s, to a flood corresponding to the 100-year flood discharge for the 1980s (mean and range of 5-11 GCMs, population constant at 2005 values)	RCP2.6: 0.4% (0.2-0.5%) RCP4.5: 0.6% (0.4-1.0%) RCP6.0: 0.7% (0.3-1.1%) RCP8.5: 1.2% (0.6-1.7%) GW 2°C: 0.5% (0.3-0.6%)	Hirabaya shi *et al.* (2013)

		GW 4°C: 1.2% (0.8-2.2%) 1980s: 0.1% (0.04-0.16%)	
Change in irrigation water demand, global scale	Change of required irrigation water withdrawals by the 2080s (on area irrigated around 2000) as compared to the 1980s (range of 3 GCMs)	RCP2.6: -0.2-1.6% RCP4.5: 1.9-2.8% RCP8.5: 6.7-10.0%	Hanasaki *et al.* (2013)
River flow regime shifts from perennial to intermittent and vice versa, global scale	Percent of global land area (except Greenland and Antarctica) affected by regime shifts between the 1970s and the 2050s (range of 2 GCMs)	SRES B2: 5.4-6.7% SRES A2: 6.3-7.0%	Döll and Müller Schmied (2012)
Water scarcity	Percent of global population living in countries with less than 1300 m^3/year of per-capita in the 2080s (mean of 17 GCMs, population constant at 2000 values)	No significant differences between SRES B1 and A2	Gerten *et al.* (2011)
New or aggravated water scarcity	Percent of global population living in river basins with new or aggravated water scarcity around 2100 as compared to 2000 (less than 1000 m^3/year of per-capita blue water resources) (median of 19 GCMs, population constant at 2000 values)	GW 2°C: 8% GW 3.5°C: 11% GW 5°C: 13%	Gerten *et al.* (2013)
Exposure to water scarcity	Population in water-stressed watersheds (less than 1000 m^3/year of per-capita blue water resources) exposed to an increase in stress (1 GCM)	For emissions scenarios with 2°C target, compared to SRES A1: 5-8% impact reduction in 2050 10-20% reduction in 2100	Arnell *et al.* (2013)
Change of groundwater recharge in the whole of Australia	Probability that groundwater recharge decreases to less than 50% of the 1990s value by 2050 (16 GCMs)	GW 1.4°C: close to 0 almost everywhere GW 2.8°C: in western Australia 0.2-0.6, in central Australia 0.2-0.3, elsewhere close to 1	Crosbie *et al.* (2013a)
Change in groundwater recharge in East Anglia, UK	Percent change between baseline and future groundwater recharge, in %, by the 2050s (1 GCM)	SRES B1: -22% SRES A1f: -26%	Holman *et al.* (2009)
Change of river discharge, groundwater recharge and hydraulic head in groundwater in two regions of Denmark	Changes between the 1970s and the 2080s (1 regional climate model)	Differences between SRES B2 and A2 are very small compared to the changes between the 1970s and the 2080s in each scenario	van Roosmalen *et al.* (2007)
River flow regime shift for river in Uganda	Shift from bimodal to unimodal (1 GCM)	Occurs in scenarios with GW of at least 4.3°C but not for smaller GW	Kingston and Taylor (2010)
Agricultural (soil	Mean duration, affected area and	Smaller increases over time	Vidal *et*

moisture) droughts in France	magnitude of short and long drought events throughout the 21st century (1 GCM)	for SRES B1 than for A2 and A1B	*al.* (2012)
Salinization of artificial coastal freshwater lake IJsselmeer in the Netherlands (a drinking water source) due to seawater intrusion	(1) Daily probability of exceedance of maximum allowable concentration (MAC) of chloride (150 mg/liter), (2) Maximum duration of MAC exceedance (2050, 1 GCM)	Reference period 1997-2007 (GW 0.8°C): (1) 2.5%, (2) 103 days GW 1.8°C, no change in atmospheric circulation: (1) 3.1%, (2) 124 days GW 2.8°C and change in atmospheric circulation: (1) 14.3%, (2) 178 days	Bonte and Zwolsman (2010)
Decrease of hydropower production at Lake Nasser, Egypt	Reduction of mean annual hydropower production by the 2080s compared to hydropower production 1950-99 (11 GCMs)	SRES B1: 8% SRES A2: 7%	Beyene *et al.* (2010)
Reduction of usable capacity of thermal power plants in Europe and USA due to low river flow and excessive water temperature	Number of days per year with a capacity reduction of more than 50% (for existing power plants) (2031-2060, 3 GCMs)	Without climate change: 16 SRES B1: 22 SRES A2: 24	van Vliet *et al.* (2012)
Flood damages in Europe (EU27)	(1) Expected annual damages, in 2006- €, (2) Expected annual population exposed (2080s, 2 GCMs)	SRES B2: (1) 14-15 billion €/year, (2) 440,000-470,000 people SRES A2: (1) 18-21 billion €/year, (2) 510,000-590,000 people Reference period: (1) 6.4 billion €/year, (2) 200,000 people	Feyen *et al.* (2012)