



A review of recent developments in climate change science. Part II: The global-scale impacts of climate change

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Abstract

This article presents a review of recent developments in studies assessing the global-scale impacts of climate change published since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). Literature covering six main impact sectors is reviewed: sea-level rise (SLR) and coastal impacts, ocean acidification, ecosystems and biodiversity, water resources and desertification, agriculture and food security, and human health. The review focuses on studies with a global perspective to climate change impacts assessment, although in the absence of global studies for some sectors or aspects of impacts, national and regional studies are cited. The review highlights three major emerging themes which are of importance for the policy- and decision-making process: (1) a movement towards

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probabilistic methods of impacts assessment and/or the consideration of climate modelling uncertainty; (2) a move towards assessing potential impacts that could be avoided under different climate change mitigation scenarios relative to a business-as-usual reference scenario; and (3) uncertainties that remain in understanding the relationship between climate and natural or human systems. Whether recent impact assessments show a changed risk of damage to human or natural systems since the AR4 depends upon the impact sector; whether the assessments are robust or not (i.e. will stand the test of time) requires additional expert judgement. However, using this judgement, overall we find an increased risk to natural systems, and in some components of human systems.

Keywords

agriculture, climate change impacts, ecosystems, health, Intergovernmental Panel on Climate Change (IPCC), ocean acidification, sea-level rise, water resources

I Introduction

Policy-makers need up-to-date information on the likely future impacts of climate change on human society and natural systems. The Fourth Assessment Report (hereafter referred to as AR4) of the Intergovernmental Panel on Climate Change (IPCC) has played a major role in framing the current understanding of likely impacts (IPCC, 2007a, 2007b). However, substantial research progress has been made since then, forming a vast body of post-AR4 scientific literature. The next comprehensive assessment by the IPCC is not expected to be published until 2013, while there are a number of policy decisions being made now which may benefit from the new information available. There is therefore a demand for experts to collate and assess this literature at more frequent and timely decision points. One form of information needed is advice on the most significant scientific advances pertinent to the evaluation of emission and global-mean temperature targets. A further general issue lies in identifying which developments are robust – i.e. will stand the test of time.

Here we present a review of recent developments in studies assessing the impacts of climate change published since the AR4. This paper complements a review presented by Good et al. (2011), which reviews recent developments in understanding of future change in the large-scale climate system. The primary purpose of the review is to support decision-makers with updated

information on the latest science on the impacts of climate change.

Specifically, the review has been prepared within the context of high-level decision-making, at the regional to global level, where decisions need to be made on mitigation and adaptation strategies to deal with the risks posed by climate change. Given this, it is important that the uncertainties associated with the latest impacts projections are adequately conveyed. A key research need highlighted by an international panel of climate change scientists recently highlighted that the projections provided to decision-makers must be accompanied by estimates of uncertainty via model ensemble runs that span uncertainties in – at a minimum – initial conditions, model parameterizations, and biophysical feedbacks (Doherty et al., 2009). This review highlights recent advances in quantifying and communicating the inherent uncertainties associated with impacts projections.

Given the high level scope of this review, we have focused on studies which present a global perspective on climate change impacts assessments, although, in the absence of this for some sectors or processes, regional and national studies are cited.

Over 100 countries have now accepted a 2°C limit for global-mean temperature rise in order to avoid ‘dangerous’ climate change, as reflected in the Copenhagen Accord, so we also

Table 1. Words used (including 'climate change', 'global warming', 'mitigation' and 'impact') for searches in Web of Science and number of citations included in the review

Impact sector	Keywords	Citations
Sea-level rise (SLR) and coastal impacts	coast; coastal; flooding; sea-level rise; SLR; adaptation; global; tourism; ecosystem	25
Ocean acidification	ocean acidification; pH; ocean; acidity; ecosystem; global; calcification	32
Ecosystems and biodiversity	ecosystem; biodiversity; plants; animals; forest; coral	58
Water resources and desertification	water resources; runoff; hydrology; water stress; desertification; drought	30
Agriculture and food security	agriculture; crops; food; food security; CO ₂ enrichment	16
Human health	health; mortality; infectious disease; malaria; dengue; heat; cold; extreme	27

review post-AR4 studies that have specifically explored the impacts of climate change for different degrees of global-mean warming. We refer in such cases to a '2°C world', for instance.

A further aim of this review is to highlight where new evidence may suggest changes in the magnitude of risk of human systems to climate change, level of understanding, and confidence, relative to the time of the publication of the AR4. Therefore we review impacts across six sectors that broadly follow those considered by Working Group II of the AR4 (the working group that assesses the vulnerability of socio-economic and natural systems to climate change) (IPCC, 2007a). The review is structured into the following six sections for each impact sector respectively, which further allows us to make recommendations for future research (Appendix I) and highlight post-AR4 emerging themes (Appendix II) accordingly:

- sea-level rise (SLR) and coastal impacts;
- ocean acidification;
- ecosystems and biodiversity;
- water resources and desertification;
- agriculture and food security;
- human health.

The literature searches were conducted through the Thomson Reuters Web of Science online

academic search engine (Web of Science, 2010). Keyword searches were conducted for each impact sector using various combinations of the words included in Table 1. Searches were limited to publications with a publication date in the range 2007–2010. Searches with the same keywords presented in Table 1 were also applied using Google Scholar.

II Sea-level rise (SLR) and coastal impacts

The AR4 estimated that global-mean SLR relative to 1980–1999 could be in the range 0.18–0.38 m for an approximately 2°C world, and 0.26–0.59 m for an approximately 4°C world (IPCC, 2007a). More recent SLR estimates that apply the 'semi-empirical' approach (Rahmstorf, 2010) corroborate the view that projections of SLR from AR4 may be underestimated and suggest a somewhat more likely higher central tendency of SLR with climate change than previously thought, but they should not be treated as definitive as or more robust than the projections of the AR4; see Good et al. (2011) for further discussion.

SLR will have impacts on human society. Nicholls (2004) – cited in the AR4 – estimated that, globally, an additional 63–102 million people would be flooded (assuming present-day

protection levels), and an additional 5–20% of coastal wetlands would be lost, due to a 34 cm global SLR relative to present. New work has attempted to further quantify the *global-scale* impact of SLR but differences in methodologies and spatial scales of analysis between studies mean that it is not possible to say whether they objectively present a change in the magnitude of impact relative to results presented in the AR4. For example, Dasgupta et al. (2009) estimated that around 56 million people and 1.86% of coastal wetlands would be lost across 84 developing countries due to a 1 m SLR. Similar to results presented by Nicholls (2004), southeast Asia was the most highly affected region. Indeed, other simulations estimated the total coastal wetland area of the Coral Triangle (Indonesian, Malaysia, the Philippines, East Timor, Papua New Guinea, and the Solomon Islands) to decrease by 26–30% (dependent upon emissions scenario) in 2100 relative to 2010, due to SLR (McLeod et al., 2010).

Recent efforts have attempted to cost the impact of global increases in SLR. Van Vuuren et al. (2010) estimated global damages of \$US400,000 million/year for a SLR of 0.71 m and Dasgupta et al. (2009) placed the cost of a 1 m SLR at around \$US220,000 million. The difference in costs is partly because Dasgupta et al. (2009) only considered developing countries.

Generally, there has been little post-AR4 research on the global-scale impact of SLR, so we recommend that future studies address this by employing broadly consistent methodologies. This is one of the 10 recommendations and suggested future research priorities highlighted from this review (see Appendix I). However, post-AR4 research provides a more detailed overview of the potential impact of SLR for cities. For instance, potential high economic and environmental costs of future SLR have been estimated for New York (Gornitz and Rosenzweig, 2009), London (Lonsdale et al., 2008), Copenhagen (Hallegatte et al., 2009),

Istanbul (Karaca and Nicholls, 2008), Mombassa (Awuor et al., 2008), Venice (Carbognin et al., 2010), Shanghai (Yin et al., 2011), and New Jersey (Cooper et al., 2008). Moreover, this reflects an emerging post-AR4 theme of exploring climate change impacts for cities, specifically (see Appendix II).

Post-AR4 research builds upon the retreat versus protection issue of coastal adaptation (see, for example, Nicholls and Cazenave, 2010). Some recent studies suggest that even with large SLR of >1 m/century it would still be economically rational to protect some developed coasts, e.g. in the Netherlands (DeltaCommission, 2008; Kabat et al., 2009) and the UK (Environment Agency, 2009; Mokrech et al., 2008). However, this would not protect smaller assets on other parts of the coastline or the coastal ecosystems. Other studies suggest retreat (Olsthoorn et al., 2008; Poumadère et al., 2008) or policy paralysis is more likely (Lonsdale et al., 2008). It is crucial that there is an awareness that climate change, together with other stressors on the coastal environment brought about by existing management practices, can produce or is producing the impacts that trigger the adaptation cycle (Tol et al., 2008). Also, in some cases, the management choices associated with coastal ecosystems can have a *greater* potential impact on habitat viability than climate change (Richards et al., 2008). Therefore the monitoring of adaptation decisions is important, along with an understanding of the benefit-cost relationship associated with them (Tol et al., 2008). For instance, Anthoff et al. (2010) considered global SLR impacts after balancing the costs of retreat with the costs of protection, and demonstrated that an optimum response in a benefit-cost sense remained widespread protection of developed coastal areas – East Asia, North America, Europe and South Asia experienced the most costs – although without the strong economic growth in the SRES scenarios the benefits of protection were significantly reduced.

III Ocean acidification

New studies confirm AR4 statements that absorption of CO₂ by the ocean has decreased ocean surface pH by 0.1 since 1750 and that it is projected to decrease by up to a further 0.3–0.4 units by 2100 in a 3–4°C world (Bernie et al., 2010; Caldeira and Wickett, 2003; Cao et al., 2007; Feely et al., 2009; IPCC, 2007a). Furthermore, the well-accepted conclusion that future changes in ocean acidification (OA) caused by emissions of CO₂ into the atmosphere are *largely* independent (although not completely) of the amounts of global-mean temperature rise has been confirmed (Cao et al., 2007).

Recent studies have addressed the potential magnitudes of declines in ocean pH that could be avoided if certain global mitigation policies are applied. Matthews et al. (2009) showed that climate engineering (as a uniform reduction of incoming solar radiation) could slow ocean pH decreases somewhat relative to a non-engineered case – their results are consistent with those of Cao et al. (2007) in that changes in temperature due to climate engineering did have secondary effects on pH and aragonite saturations, compared to anthropogenic CO₂ emissions. Bernie et al. (2010) suggested that under a mitigation policy with peaking global emissions in 2016 and a post-peak reduction of 5% per year to a low long-term emissions floor (6GtCO₂e/yr), pH could be maintained at 8.02 in 2100 (7.81 under A1B emissions), compared with pre-industrial and present-day values of 8.16 and 8.07 respectively. While this represents a considerable reduction in the magnitude of pH decrease relative to a non-mitigation scenario, it still represents a significant further acidification relative to pre-industrial levels.

Post-AR4 research provides a more regionally detailed overview of the impacts of OA because, previously, the majority of studies focused either on global average conditions (Caldeira and Wickett, 2003) or on low-latitude regions (Kleypas et al., 1999). For instance, simulations

suggest that under SRES A2 emissions the Arctic ocean will start to become undersaturated with respect to aragonite by 2020 (Steinacher et al., 2009), and that by 2050 all of the Arctic will be undersaturated, and by 2095 all of the Southern Ocean and parts of the North Pacific will be undersaturated (Feely et al., 2009). This supports the conclusions of the AR4 that the Southern Ocean is an area of high risk. Also, OA has been projected to trigger marine oxygen holes (Hofmann and Schellnhuber, 2009); marine areas depleted in oxygen currently occur as a result of pollution and cause ‘dead zones’.

Research into the impacts of OA on non-coral organisms has expanded post-AR4. Much focuses on fish, although there are still several knowledge gaps (Cobb, 2010; Wilson et al., 2010). Evidence suggests OA can impair fish hearing and balance (Checkley et al., 2009), sense of smell (Munday et al., 2009), and sensing of predators (Munday et al., 2010). SLR will likely have a material impact on fish populations in synergy with other stressors such as rising sea surface temperature, e.g. climate change may lead to large-scale redistribution of global fish catch potential, with an average of 30–70% increase in high-latitude regions and a drop of up to 40% in the tropics, in 2050 (Cheung et al., 2010). New evidence shows that OA negatively affects commercially valuable calcifying organisms such as mussels and oysters (Gazeau et al., 2007; Kurihara et al., 2007, 2009). Developing nations in the Pacific rely on such organisms for about 7–20% of their catches and many of the small island states that comprise this region have limited agricultural alternatives for the provision of income and protein (Cooley et al., 2009). Moreover, global fisheries associated with coral reefs are valued at US\$5.7 billion annually (Conservation International, 2008).

The AR4 acknowledged that some organisms appear to be unaffected by OA and some negatively affected. Evidence published post-AR4 supports this (Hendriks et al., 2010; Ries

et al., 2009) and recent studies demonstrate that calcification and net primary production may be significantly increased by high CO₂ partial pressures (Iglesias-Rodriguez et al., 2008; Rodolfo-Metalpa et al., 2010; Wood et al., 2008), which contradicts several previous studies (Leonardos and Geider, 2005; Riebesell, 2008; Riebesell et al., 2000; Sciandra et al., 2003). However, such discrepancies are likely due to inconsistent methodological approaches (Ridgwell et al., 2009) and while some organisms can increase the rates of many of their biological processes in response to OA, this can come at a substantial cost (muscle wastage) and is therefore unlikely to be sustainable in the long term (Hall-Spencer et al., 2008; Wood et al., 2008). Given the inconsistencies, it is not possible to state with a higher degree of confidence than given by the AR4 (medium confidence) (Fischlin et al., 2007) the magnitude of the impact that OA will have on marine organisms in general and how resistant they will be to increased OA. Future research should provide a more detailed understanding of the varied responses of OA on different marine organisms through the application of consistent methodologies (see Appendix I).

IV Ecosystems and biodiversity

Table 2 summarizes post-AR4 research on climate change impacts on global ecosystems. The range of impacts is diverse, which prompts Galaz et al. (2008) to argue that the potential for abrupt negative changes in ecosystems and associated ecosystem services, due to climate change, combined with their ability to trigger large-scale crises and human migration, and to cause rapid-onset shocks with serious economic and social repercussions, should be among the main priorities for the international climate-policy community.

Studies continue to support the AR4 statement that 'approximately 20–30% of plant and animal species assessed so far ... 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' (IPCC, 2007a; Warren et al., 2011). Poleward shifts in polar and boreal ecosystems show the greatest change (Colwell et al., 2008). Studies continue to emphasize the sensitivity of mountains (Nogues-Bravo et al., 2007), which often hold range-restricted species with limited dispersal abilities (Engler and Guisan, 2009), especially in the tropics (Wake and Vredenburg, 2008).

Marked changes in marine and freshwater ecosystems have now been detected; in particular organism life-cycle changes and several studies have investigated the impacts of sea surface temperature and acidification on corals (see section III). Figueira and Booth (2010) and Stuart-Smith et al. (2010) address the post-AR4 gap in empirical data on community-level responses (other than corals) to rising water temperatures. They highlight less severe impacts than what is expected for coral reefs and they suggest community responses to ocean warming may follow non-linear, step-like trajectories.

There have been several advances in understanding the impact on forests. Recent observations demonstrate a high vulnerability to future drying of Amazonia as well as potential for large carbon losses to exert positive feedback on climate change (Da Costa et al., 2010; Phillips et al., 2009, 2010). However, modelling studies demonstrate high uncertainty in projections of Amazonia die-back associated with the CO₂ fertilization effect (see Table 2), which presents an important area for future research (see Appendix I). Moreover, new studies document widespread forest mortality worldwide due to climatic water and heat stress (Adams et al., 2009; Allen et al., 2010; Raffa et al., 2008). Also, simulations suggest long-term committed forest loss is underestimated by models because the global terrestrial biosphere can continue to change for decades after climate stabilization (Jones et al., 2009).

Table 2. Summary of post-AR4 climate change impacts on global ecosystems

Ecosystem	Impact
Marine and freshwater	<ul style="list-style-type: none"> • Sea temperature rises have triggered poleward movement of warm-water species and retreat of colder-water species, as fast as 15–50km/decade (Wetthey and Woodin, 2008); or retreat to deeper cooler water (Dulvy et al., 2008) • Climate change may lead to numerous local extinctions in some regions and invasion in others, together resulting in dramatic species turnovers (i.e. invasion to and extinction from an area) of over 60% of the present biodiversity (Cheung et al., 2009) • Many marine species now appear earlier in their seasonal cycles (EEA, 2008) and life-cycle changes have been observed in several marine species, e.g. turtles (Mazaris et al., 2008)
Tropical species	<ul style="list-style-type: none"> • Wright et al. (2009) found that 20% of tropical mammal species would have to travel >1000 km to a cool refuge under moderate climate change compared with only 4% of small-ranged extra-tropical mammal species
Coral reefs	<ul style="list-style-type: none"> • Declines in abundance and extent of coral reefs associated with increased bleaching and disease events have now been shown to be largely driven by elevated sea surface temperatures (Lough, 2008) • Tropical storms are limiting recruitment and survival of non-branching corals (Crabbe, 2008) and a third of coral reefs face elevated extinction risk today based on current rates of decline (Carpenter et al., 2008) • Acidification and sea surface temperature rise is projected to lead to widespread decline of reef-building corals and the thousands of species which they support (Anthony et al., 2008; Cao and Caldeira, 2008; Guinotte and Fabry, 2008; Veron, 2008; Veron et al., 2009)
Polar	<ul style="list-style-type: none"> • Still considered among the most vulnerable ecosystems to climate change, with large potential losses of tundra (Wolf et al., 2008) and declines in sea-ice-dependent species (Clarke et al., 2007) • Polar bears are projected to lose 68% of their summer habitat by the 2090s in the absence of greenhouse gas emission reductions (Durner et al., 2009) • Antarctic emperor penguin population size could decline from around 6,000 breeding pairs in present to ~2300 in 2030, to ~1500 in 2060, and to ~400 in 2100 (Jenouvrier et al., 2009), and if global-mean warming reaches 2°C, emperor penguin populations north of 70°S could disappear (Ainley et al., 2010)
Forests	<ul style="list-style-type: none"> • Since the AR4, it has been found that old growth forests continue to store carbon rather than being carbon neutral (Luyssaert et al., 2008) and tropical forests are increasing the amount of carbon which they store annually as a result of climate change (Lewis et al., 2009) • There is now greater confidence in projections of Amazon drying (Malhi et al., 2009) and dieback; 18–70% of forest could be lost or converted to seasonal forest under climate change (Huntingford et al., 2008). However, the magnitude of dieback is highly dependent on assumptions about the CO₂ fertilization effect (Lapola et al., 2009; Rammig et al., 2010)

Confirming findings in AR4, phenological changes have been seen in trees, plants, fungi, amphibians and birds (Gordo, 2007; Kusano and Inoue, 2008). Changes are stronger at higher

northern latitudes (Colwell et al., 2008). Unsynchronized phenological changes have resulted in population reductions due to mismatches between predators and their prey (e.g. first insect

appearance and the arrival of migrant birds; Zalakevicius et al., 2006), and in polar regions (Post et al., 2009). Climate change impacts on species composition of communities have been observed in several locations in widely different ecosystem types (Moritz et al., 2008), further supporting AR4 statements to this effect, while regime shifts have been detected in marine food webs as a result of observed changes in sea surface temperature (Alheit, 2009).

There is growing concern for dealing with emissions and climate model uncertainty within biome/ecosystem modelling (Salazar et al., 2007; Zaehle et al., 2007) and species distribution modelling (Dormann et al., 2008; Fitzpatrick et al., 2008), which reflects the inherent uncertainty of climate change modelling. Also, the use of ensemble forecasting techniques is an increasing trend, which enhances precision of projected ecosystem and biodiversity impacts (Araujo and New, 2007; O'Hanley, 2009).

Post-AR4 studies also demonstrate the importance of climate change impacts on urban biodiversity. For example, Hellmann et al. (2010) showed that the synergistic effects of climate and land-use change will negatively affect some organisms, while for others a mixed landscape mosaic of interconnected green spaces may actually be beneficial. Moreover, rising CO₂ levels in cities, combined with a warmer climate and CO₂ fertilization, will affect urban biodiversity (Nowak, 2010), including the spread of exotic species (Niinemets and Peñuelas, 2008), with important implications for urban vegetation and biodiversity management (Gill et al., 2008; Kithiia and Dowling, 2010). Generally, this reflects an emerging post-AR4 theme of exploring climate change impacts for cities, specifically (see Appendix II).

V Water resources and desertification

The AR4 concluded that, globally, climate change will have an overall net negative

impact on water resources (high confidence) (Kundzewicz et al., 2007). New results confirm AR4 findings that more people will experience decreased water scarcity under climate change than experience an increase (Hayashi et al., 2010). However, most post-AR4 research focuses on increased water scarcity. For instance, Rockstrom et al. (2009) showed that in an approximately 2°C world around 59% of the world's population would be exposed to 'blue water shortage' (i.e. irrigation water shortage) but this was based upon only a single climate projection, and so overlooks climate modelling uncertainty.

An emerging post-AR4 theme is a more detailed consideration of climate modelling uncertainty in water resources modelling. Preston and Jones (2008) used 12 AR4 climate models to estimate change in runoff per degree of global-mean warming for Australia. They noted high uncertainty but it does provide an example of an attempt to generalize impact assessment results away from the raw driving climate projections to draw general conclusions about rates of change. Simulations using an updated version of the hydrological model applied in the AR4 (Gosling and Arnell, 2011) showed that for a 2°C world 0.570–1.960 billion people (range across four climate models) (Arnell et al., 2011) or 0.304–2.202 billion (range across 21 climate models) (Gosling et al., 2010) might experience increased water scarcity. These present a comparable but wider range than presented in the AR4 (0.670–1.538 billion people, across six climate models) (Arnell, 2004; Kundzewicz et al., 2007) due to the application of more and different forcing climate models. Moreover, new evidence suggests that climate model uncertainty is substantially greater than hydrological model uncertainty or emissions uncertainty (Gosling et al., 2011; Kay et al., 2009).

A post-AR4 development is the consideration of the potential 'benefits' that certain mitigation policy scenarios might have on water scarcity.

Recent experiments that apply climate change projections from multiple climate models suggest that up to 20–65% of global increased water scarcity impacts could be avoided by the end of the 21st century under mitigation scenarios, relative to business-as-usual scenarios (Arnell et al., 2011; Fischer et al., 2007; Gosling et al., forthcoming). These studies show that climate policy reduces, but does not eliminate, the impacts of climate change. In stark contrast, Hayashi et al. (2010) observed higher global water scarcity in a mitigation scenario than in a business-as-usual scenario, largely due to precipitation increases in southeast Asia, but their estimate overlooks the effects of climate model uncertainty, so the results should not be considered as robust as the others.

The AR4 projected that drought-affected areas are likely to increase in extent in the future, with Europe, the Mediterranean, and southern areas of Australia at particular high risk in summer months. New results confirm this for the Mediterranean, based upon simulations applying single (de Dios et al., 2009; Gao and Giorgi, 2008) and multiple climate models (Giorgi and Lionello, 2008; Gosling et al., 2010; Sheffield and Wood, 2008), meaning that extensive irrigation will be required in the region to adapt to the less favourable agricultural conditions (Gao and Giorgi, 2008; Sillmann and Roeckner, 2008). Furthermore, a critical risk area for drought in south and southeastern Europe has now been identified (Planton et al., 2008), although a study that explored mitigated and unmitigated climate change scenarios demonstrated that this could dramatically be reduced by stringent mitigation action (Warren et al., forthcoming). Moreover, significant increases in drought have also been projected for West Africa, central Asia, Central America, western Australia, the Middle East, Indochina and mid-latitude North American regions (Hirabayashi et al., 2008; Sheffield and Wood, 2008; Sillmann and Roeckner, 2008).

New research highlights the importance of management in adapting to and mitigating

climate change impacts on water scarcity. Vorosmarty et al. (2010) showed that in 2000 nearly 80% (4.8 billion) of the world's population was exposed to high levels of threat to water security, and that 65% of global river discharge, and the aquatic habitat supported by this water, was under moderate to high threat. A key conclusion was that globally, while water security increases with affluence, so do threats to biodiversity – the actions taken to reduce water scarcity (e.g. dam construction and flow diversions) typically result in habitat loss and reductions in fish diversity and water quality. Establishing human water security for the first time across the developing world, and adapting and mitigating to the impacts elsewhere – at the same time while preserving biodiversity – presents a dual challenge that will require integrated water resource management that specifically balances the needs of humans and nature (Palmer, 2010). This is a key future research priority (see Appendix I).

There is also more detail on the impact of climate change on urban water resources. Much like recent advances in global modelling, there is greater quantification of climate model uncertainty in modelling projections (Charlton and Arnell, 2011; Manning et al., 2009; O'Hara and Georgakakos, 2008; Raje and Mujumdar, 2010), as well as a more comprehensive understanding of adaptation management from city-specific case studies (Covich, 2009; Praskievicz and Chang, 2009; Van der Bruggen et al., 2010; Ziervogel et al., 2010). Moreover, this reflects an emerging post-AR4 theme of exploring climate change impacts for cities, specifically (see Appendix II).

VI Agriculture and food security

Research into the effects of CO₂ fertilization under climate change scenarios has expanded since the AR4. The AR4 highlighted understanding of the effect of enriched CO₂ concentrations on crop productivity as a key area for future research and concluded that while Free-

Air Carbon Dioxide Enrichment (FACE) studies show crop productivity is projected to decrease for small local temperature increases (1–2°C) at low-latitude and tropical regions, it is projected to increase slightly for warming of 1–3°C at mid- to high latitudes, depending on the crop, and increase globally, but above this temperature it is projected to decrease (IPCC, 2007a).

Research published shortly after the AR4 suggests the generally positive effect of CO₂ enrichment on crop productivity may be offset by changes in pests, weeds, diseases and extreme events (Tubiello et al., 2007), elevated ozone concentrations (e.g. from anthropogenic emissions) (Booker et al., 2009; Reilly et al., 2007; Van Dingenen et al., 2009), and high temperature extremes (Aggarwal, 2008; Challinor and Wheeler, 2008). The reduced protein content of crops associated with elevated CO₂, highlighted as ‘new knowledge’ at the time of AR4 publication, is supported by new results; Ainsworth and McGrath (2010) demonstrated that grain quality, protein content and mineral concentration is adversely affected by elevated CO₂.

This slightly less-optimistic-than-AR4 outlook for global crop production is supported by Tebaldi and Lobell (2008). The authors applied probabilistic methods to demonstrate that projected changes in temperature and precipitation negatively affect global crops yields by causing a decrease in yield of about 9% (with 95% probability intervals of 1.7–17%) for barley, of 13% (5–25%) for maize and of 5% (1–10%) for wheat. Including CO₂ fertilization reduced projected losses by an average of 7% for wheat and barley but did not change significantly the impact on maize. The study considered a time frame of 2030 when CO₂ levels are expected to reach around 450 ppm and they estimated at most a 75% chance that CO₂ and climate effects will cancel by 2030 for wheat, at most a 30% chance for barley, and 0% for maize. Given this, the authors conclude that the AR4 statement that global yields of C3 crops will be unaffected at 550 ppm appears optimistic, although within

their fairly wide uncertainty bounds. In stark contrast, Hayashi et al. (2010) estimated that global wheat (rice) production potential relative to 1990 will increase approximately 20% (40%) in 2050, 20% (50%) in 2100, and 8% (50%) in 2150, but this estimate was based upon climate projections from a single climate model and emissions scenario, so is less robust than the estimates presented by Tebaldi and Lobell (2008). Nevertheless, the likelihood of positive effects of CO₂ enrichment on crop productivity under climate change scenarios should be further explored and understood (see Appendix I).

Other post-AR4 studies apply probabilistic assessment to provide a more comprehensive treatment of uncertainty, including, for instance, emissions uncertainty, climate modelling uncertainty and crop modelling uncertainties. Lobell et al. (2008) highlighted that without adaptation measures south Asia and southern Africa will likely suffer negative impacts on several crops and Li et al. (2009) demonstrated that, globally, drought disaster-affected area will increase with climate change from 15% at present to 44% by 2100, increasing rates of yield reduction for major crops by almost 90%. Probabilistic assessments imply that while careful comparison of simulations with observations may dampen climate-crop modelling uncertainty, it is only through understanding and simulating climate-crop processes at local and regional levels, and at appropriate levels of complexity, that the impacts of climate change can be assessed to inform decisions on local adaptation planning (Challinor et al., 2009; Thornton et al., 2009).

The AR4 briefly highlighted the potential benefits that mitigation policy could have on crop production (Tubiello and Fischer, 2007). Post-AR4 research explores this in more detail (McCarl, 2010). Falloon and Betts (2010) showed that changes in future hydrology and water management practices will influence agricultural adaptation measures and alter the effectiveness of agricultural mitigation strategies. Adaptation in the water sector could potentially

provide additional benefits to agricultural production such as reduced flood risk and increased drought resilience.

VII Human health

With the exception of a couple of global assessments (Bosello et al., 2006: not cited in the AR4; Hayashi et al., 2010), the majority of post-AR4 climate change temperature-mortality studies are for individual cities (Chang et al., 2010; Gosling et al., 2009c; Hayhoe et al., 2010; Knowlton et al., 2008; Muthers et al., 2010), which adds further detail to AR4 coverage. However, an important development is that post-AR4 observational and modelling studies highlight that methodological approaches mean that previous assessments might have underestimated the number of heat-related deaths attributable to climate change and climate variability. For instance, Robine et al. (2008) calculated that more than 70,000 additional deaths occurred during the European 2003 heat wave, instead of the 30,000 estimated previously (UNEP, 2004). Modelling studies reported in the AR4 assumed only the mean temperature changes under climate change, with the variability remaining unchanged. New work shows this assumption is unrealistic (Ballester et al., 2010) and, moreover, simulated heat-related mortality with climate change may be up to twice as large when climate variability is accounted for, relative to considering mean temperature change only (Gosling et al., 2009a, 2009c).

The AR4 concluded that additional research is needed to understand how the balance of heat- and cold-related mortality could be affected by climate change. Post-AR4 research suggests that increased temperatures would *reduce* global heat-related mortality as reductions in cold-weather mortality more than offset increases in hot-weather mortality (Bosello et al., 2006: not cited in the AR4; Hayashi et al., 2010). However, these results are based upon temperature-related mortality estimates

from Tol (2002), which Ackerman and Stanton (2008) argue account appropriately neither for geographic variability in tolerance nor for the countervailing effect of human adaptation, which other studies have shown to be important (Gosling et al., 2009b, 2009c; Meze-Hausken, 2008). As such, the credibility of the assertion that global temperature-related deaths may decrease with climate change is debatable and remains a key area for future research (see Appendix I). Also, the aggregation of national mortality to the global scale hides important regional variations.

A recent review paper argued that there is a high degree of uncertainty associated with the impacts of climatic extremes (other than temperature) – e.g. wildfires and hurricanes – on health and, as such, does not suggest there is any new evidence post-AR4 to indicate a change in damage from extreme events under climate change scenarios (Mills, 2009). Given that the AR4 acknowledges that there has been little additional research on the health effects of other extreme weather events since the IPCC Third Assessment Report (TAR), we highlight, along with others (Kovats and Akhtar, 2008) that there is a need to better describe the risks to health from extreme weather events.

The AR4 estimated that for an approximately 2°C world, 5–6 billion people would be at risk of dengue as a result of climate change, compared with 3.5 billion people in the absence of climate change (Confalonieri et al., 2007; Hales et al., 2002). No studies published since the AR4 have assessed the impact of climate change on dengue alone at the global level but several studies have explored malaria incidence. Chaves and Koentraadt (2010) present evidence to counteract the conclusions from a highly cited study (Hay et al., 2002), which concluded malaria incidence has increased in the apparent absence of climate trends in the Kericho highlands of western Kenya. This is supported by new work that suggested climate change may play a stronger role on malaria incidence than previously thought

(Wandiga et al., 2010). However, recent studies show non-climatic factors are also important determinants (Chaves and Koenraadt, 2010; Linard et al., 2009; Wandiga et al., 2010).

Recent modelling studies have made quantitative estimates of the potential impact of climate change on malaria. Hayashi et al. (2010) estimated that climate change could cause around 85,000–100,000 extra deaths in sub-Saharan Africa due to malaria and dengue in 2050 and van Vuuren et al. (2010) showed that malaria deaths across Africa could increase by around 100,000 in 2050 from 1 million in 2000. The application of different climate scenarios and malaria models explains the difference in results between these two studies. Moreover, Peterson (2009) demonstrated that malaria vectors in Africa are likely to see less suitable conditions across portions of West Africa with climate change, due to large, unfavourable temperature increases of 1.5–2.7°C, but improved conditions in regions of southern Africa where annual mean temperatures increase sufficiently to permit the species to establish populations.

The exploration of the potential benefits of mitigation for health impacts is an expanding area. Haines et al. (2009) showed that switching to low-carbon fuels, lowering consumption of animal products, and using clean-burning cookstoves could reduce the burden of disease on national to regional scales. Hayashi et al. (2010) estimated that globally around 1 million heat-related deaths could be avoided by 2100 if CO₂ levels are stabilized at 450 ppm relative to 650 ppm. Others studies demonstrate that limiting global warming to 2°C could reduce malaria health risks by about 2% relative to a 4°C world (van Vuuren et al., 2010) and heat-related mortality by up to 70% (Gosling and Lowe, forthcoming).

VIII Synthesis and conclusions

Recommendations and priorities for future research based upon the review of each impact

sector are presented in Appendix I. Appendix II summarizes the main post-AR4 emerging themes for each sector. Moreover, three general post-AR4 emerging themes can be drawn from the review and these comprise the final three recommendations for future research (see Appendix I).

First, the application of probabilistic methods and/or the consideration of climate modelling uncertainty are now becoming more apparent in impacts assessment. Examples cited here include crops, water resources and ecosystems modelling, although the number of studies applying such methods is relatively low compared with those that still consider impacts with climate projections from only a small number of climate models (less than three). The consideration of climate model uncertainty still remains largely absent in health impacts modelling for instance. Importantly, the conclusions drawn from a probabilistic assessment can be different from those drawn from a non-probabilistic assessment. The uncertainties associated with projections across different climate models can be large (e.g. for precipitation), so we recommend that future impact assessments adequately address this source of uncertainty, where possible (see Appendix I). Furthermore, the inclusion of other uncertainties, such as impact model uncertainty, population uncertainty and adaptation uncertainty, can reduce the significance of the climate modelling uncertainty, which when combined with probabilistic assessments methods can essentially reduce uncertainty for decision-making, and in any case be more realistic and relevant for decision-makers. This will allow for a more informed policy- and decision-making process.

Second, a major post-AR4 development that this review has highlighted is a movement towards assessing the impacts that could be avoided under different climate change mitigation scenarios, relative to a business-as-usual reference scenario. In many ways, this reflects a shift towards using climate change impacts

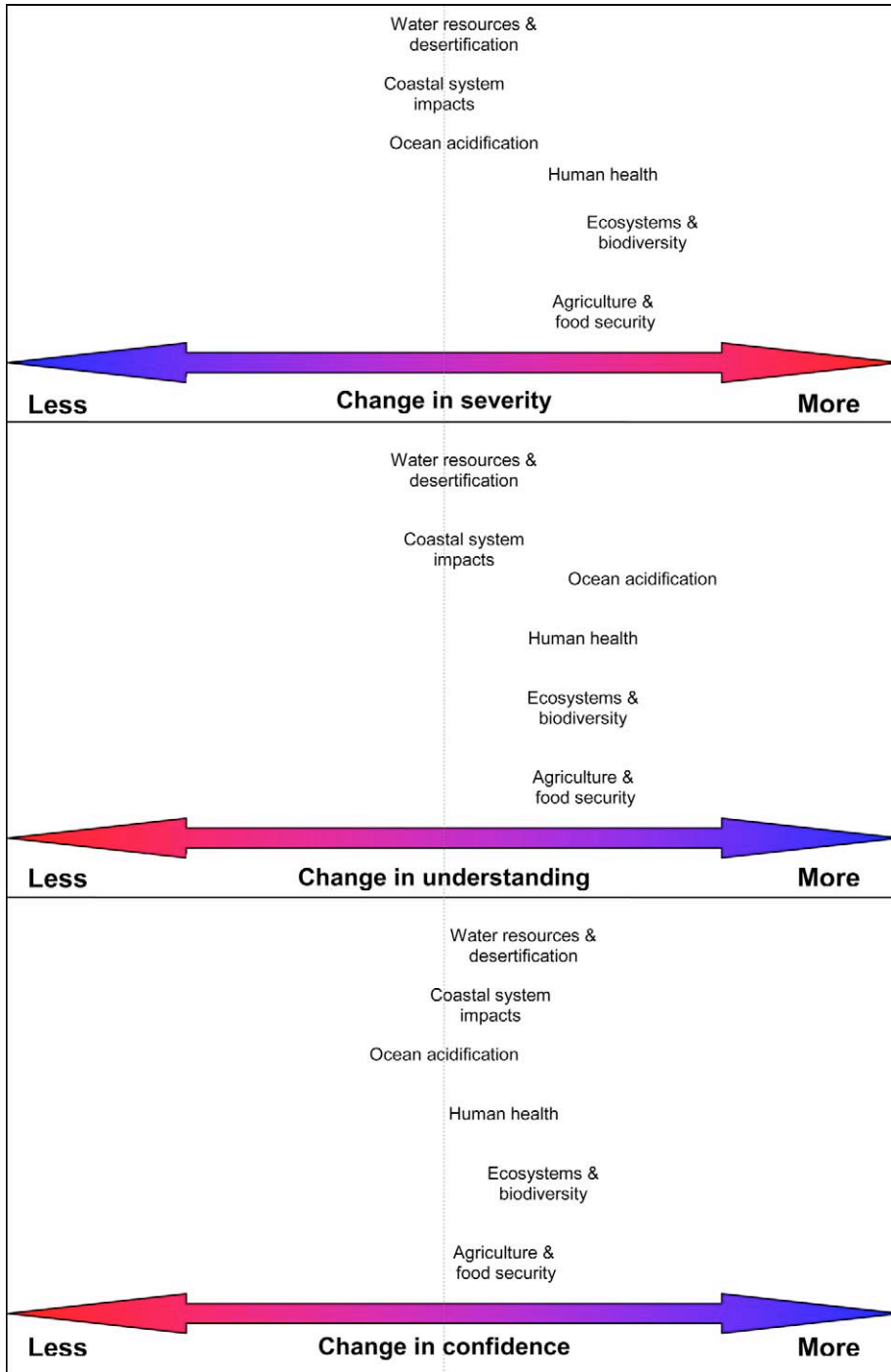


Figure 1. Summary of changes in severity, understanding and confidence regarding the impacts sectors discussed in this paper, relative to the AR4

science to inform policy- and decision-making. Across the impact sectors we considered here, such policies generally show that mitigation reduces the magnitude of the impacts relative to the reference scenario, but it does not eliminate them. In some cases the relative difference in impacts may be large and so this can provide an evidence base for recommending mitigation, which means future research into this area could be helpful (see Appendix I). However, given that mitigation does not eliminate impacts, adaptation is still an important factor and new research is starting to include different adaptation options within their modelling frameworks. Importantly, adaptation options should be considered carefully, such that they balance the needs of humans and nature.

Third, this review has shown that there are still several uncertainties in understanding the association between climate and natural or human systems; key uncertainties regard the role of CO₂ enrichment on crop productivity and Amazonia dieback, and understanding the varied response of calcifying organisms to ocean acidification, for instance.

Figure 1 summarizes, relative to what was reported in the AR4; (1) whether the degree of the severity of the impacts sectors we considered has changed; (2) whether the degree of understanding in those impacts has changed; and (3) whether the confidence in those impacts projections has changed. We assessed (1) by comparing pre- and post-AR4 impacts estimates for similar degrees of global-mean warming, (2) by evaluating what new knowledge post-AR4 research has added, and (3) by considering the degree of consensus across impacts estimates of post-AR4 findings. We acknowledge that this schematic is subjective and representative only of the views of the authors, but it makes an attempt to summarize and assess post-AR4 developments in climate change impacts science. Furthermore, we do not seek to quantify the magnitude of 'more' and 'less' on the axis, although the extreme ends of each axis may be

seen as representative of ground-breaking new developments in understanding, or of major changes in the sign of the severity of impacts since the AR4, for instance. It can be concluded from Figure 1 that the level of changed risk of damage to human or natural systems since the AR4 depends upon the impact sector; however, we find an overall increased risk to human health, ecosystems and biodiversity, and agriculture and food security. This is broadly in agreement with Smith et al. (2009), who concluded that, compared with results reported in the TAR, smaller increases in global mean temperature are now estimated to lead to significant or substantial consequences in the five 'reasons for concern' (more commonly known as the 'burning embers diagram') that were identified in the TAR.

Embedded within all the projections we reviewed, there is always a degree of uncertainty associated with our understanding of the physical processes, the impacts models and the climate models applied to them (for example, see also Kriegler et al., 2009). Some studies account for this explicitly through a probabilistic approach, while others do not. It is therefore important that future studies adequately acknowledge this in their projections so as to give an indication of the width of the uncertainty range surrounding their estimates.

The evidence shows significant changes ahead for many aspects of human and natural systems, many of them unprecedented in the course of human existence, but does not point to a definitive and obvious target for mitigation. Policy-makers must incorporate this evidence alongside other judgements such as economic, technological and social feasibility when setting strategies for tackling climate change.

Appendix I

Ten recommendations and suggested future research priorities highlighted from this review:

- (1) There has been little post-AR4 research on the global-scale impact of sea-level rise – studies that employ consistent methodologies should address this.
- (2) Future research should provide a more detailed understanding of the varied responses of ocean acidification on different marine organisms through the application of consistent methodologies.
- (3) The role of CO₂ fertilization on Amazonia dieback needs to be better understood.
- (4) Studies on the impact of climate change on global runoff and water resources should address pressing socio-ecological questions that relate to enhancing human water security.
- (5) Moreover, management decisions on mitigation and adaptation to impacts should be considered carefully so that they address both the needs of humans and the natural environment, across all impact sectors.
- (6) The likelihood of positive effects of CO₂ enrichment on crop productivity under climate change scenarios should be further explored and understood.
- (7) New methods should investigate the contention that lower cold-related mortality could offset increased heat-related mortality with climate change.
- (8) Future climate change impact assessments should adequately address the issue of climate modelling uncertainty, where possible, as well as uncertainties associated with changes in future GDP and population growth.
- (9) These and other uncertainties should be communicated through probabilistic assessment.
- (10) Future assessments should demonstrate the impacts associated with different climate change mitigation-policy scenarios relative to business-as-usual scenarios to aid decision-making processes.

Appendix II

Emerging post-AR4 themes for each sector reviewed:

SLR and coastal impacts

- Management choices associated with coastal ecosystems can have a *greater* potential impact on habitat viability than climate change.
- Post-AR4 research builds upon the retreat versus protection issue of coastal adaptation.
- More detailed case studies of the potential impact of SLR on coastal cities is now available.

Ocean acidification

- Mitigation could reduce the degree of ocean acidification but the pH changes would still represent a significant further acidification relative to pre-industrial levels.
- Methodological inconsistencies mean that it is not possible to state with a higher degree of confidence than given by the AR4 (medium confidence) the magnitude of the impact that ocean acidification will have on marine organisms in general and how resistant they will be to increased ocean acidification.

Ecosystems and biodiversity

- There have been several advances in understanding the impact of climate change on forests.
- There is more evidence that acidification and sea surface temperature rise is projected to lead to widespread decline of reef-building corals and the species which they support.
- New research highlights challenges in the management of urban ecosystems and biodiversity due to land-use and climate changes.

Water resources and desertification

- Globally, while water security increases with affluence in the present-day climate, so do threats to biodiversity.
- Mitigation could reduce but not eliminate the impact of climate change on global increased water scarcity.
- There is now more detail on the impact of climate change on urban water resources, with greater quantification of climate model uncertainty, as well as a more comprehensive understanding of adaptation management.

Agriculture and food security

- Post-AR4 assessments are starting to provide a more comprehensive treatment of uncertainty, including emissions uncertainty, climate modelling uncertainty and crop modelling uncertainties, by means of probabilistic assessment.

Human health

- Post-AR4 assessments demonstrate that changes in temperature variability can be at least as important as changes in mean temperature for temperature-related mortality and there is controversial evidence that decreased cold-deaths might offset increased heat-deaths.
- The majority of post-AR4 climate change temperature-mortality studies are for individual cities, which adds further detail to AR4 coverage.

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