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The implications of climate policy for the impacts of climate change on global water resources

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ABSTRACT

This paper assesses the implications of climate policy for exposure to water resources stresses. It compares a Reference scenario which leads to an increase in global mean temperature of 4 °C by the end of the 21st century with a Mitigation scenario which stabilises greenhouse gas concentrations at around 450 ppm CO_2e and leads to a 2 °C increase in 2100. Associated changes in river runoff are simulated using a global hydrological model, for four spatial patterns of change in temperature and rainfall. There is a considerable difference in hydrological change between these four patterns, but the percentages of change avoided at the global scale are relatively robust. By the 2050s, the Mitigation scenario typically avoids between 16 and 30% of the change in runoff under the Reference scenario, and by 2100 it avoids between 43 and 65%. Two different measures of exposure to water resources stress are calculated, based on resources per capita and the ratio of withdrawals to resources. Using the first measure, the Mitigation scenario avoids 8–17% of the impact in 2050 and 20–31% in 2100; with the second measure, the avoided impacts are 5–21% and 15–47% respectively. However, at the same time, the Mitigation scenario also reduces the positive impacts of climate change on water scarcity in other areas. The absolute numbers and locations of people affected by climate change and climate policy vary considerably between the four climate model patterns.

1. Introduction

The ultimate goal of climate policy, as stated in the UN Framework Convention on Climate Change, is to “prevent dangerous anthropogenic interference with the climate system.” (article 2) (UNFCCC, 1992). Whether interference is dangerous obviously depends on the type and degree of climate impacts. An important area where impacts may occur is the availability of fresh water resources (Alcamo et al., 2007; Arnell, 2004; Parry et al., 2007; Vörösmarty et al., 2000). Climate change will influence precipitation and evaporation patterns, and thus, indirectly, factors like local water availability, river discharge, and the seasonal availability of water supply. So far, studies have mostly concentrated on assessing the impacts of scenarios without climate policy. The most important reason is that detailed descriptions of climate change, needed as input to assess the impact on water resources, are predominantly available for scenarios that explore the consequences of different socio-economic development pathways in the absence of climate policy (Moss et al., 2010; Nakicenovic et al., 2000). Relatively few studies in the water sector (e.g. Arnell et al., 2002; Fischer et al., 2007a,b; Tubiello & Fischer, 2007; Hayashi et al. (2010)) have specifically examined the impacts avoided by policies to curb global temperature changes versus non-action – and indeed there have been very few studies in other sectors (e.g. Krol et al., 1997; Nicholls & Lowe, 2004; Bakkenes et al., 2006). With the exception of Krol et al. (1997) and Hayashi et al. (2010), these studies have considered relatively “weak” climate policies, stabilising at 750 or 550 ppm CO_2 or CO_2eq.

The aim of this paper is to assess the effects of an aggressive mitigation policy on the regional and global impacts of climate change on water resources. This mitigation policy stabilises CO_2eq concentrations at approximately 450 ppm with the aim of restricting the increase in global temperatures to 2 °C above pre-industrial. This scenario is comparable to the scenarios included in the lowest radiative forcing category in the mitigation volume of IPCC’s Fourth Assessment Report (AR4) (Fischer et al., 2007a,b). The scenario is, however, much lower in terms of radiative forcing than the climate model calculations assessed in AR4 (IPCC, 2007); these concentrated on the scenarios provided by IPCC’s Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000), none of which includes climate policy. Impacts under this policy are compared to impacts under a reference “business-as-usual” energy use scenario with no explicit attempt at climate

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mitigation. This business-as-usual scenario leads to a warming of 4 °C above pre-industrial in 2100, and is representative of the mean of the scenario literature on scenarios that have no policy intervention. The 2 °C and 4 °C have become iconical numbers in the discussion of climate policy. Both scenarios and their associated assumptions about population and rates of economic development, were constructed for the EU-funded ADAM project (van Vuuren et al., 2010). The scenarios are discussed in more detail in Section 2.

Uncertainty plays an important role in the assessment of impacts of climate change. Two factors that have complicated the assessment of water scarcity impacts are the pattern of precipitation changes and indicators that are used to define water scarcity. Complex climate models generally show that climate change leads to areas with increases and decreases in precipitation. These patterns are different across the different climate models, with only a few areas where models show similar results. In terms of water scarcity definition, two main definitions are used based on water availability alone and on the ratio between water availability and water use. This paper determines the impacts of the reference and mitigation scenarios with both water scarcity indicators, and represents the effects of climate model uncertainty by using four different patterns of climate change.

2. Methods and scenarios

2.1. Introduction

The basic methodology applied in this paper is based on two scenarios that have recently been developed in the context of the EU-funded ADAM project using the IMAGE integrated assessment model (Bouwman et al., 2006). The IMAGE integrated assessment model aims to assess possible trends in population and the economy, energy and food production, land use and land cover, emissions, the climate system and possible climate impacts. The model is comparable to a set of process-oriented integrated assessment models such as MESSAGE and GCAM that have been used extensively for scenario development, including the IPCC SRES scenarios (Nakicenovic et al., 2000). Most socio-economic trends in the IMAGE model are described for 24 or 26 regions; many environmental variables are described at a 0.5° × 0.5° grid.

The first scenario in this study explores the development of emissions in the absence of climate policy. The emission development of this scenario compares well to other ‘‘baseline’’ scenarios published in the literature and leads to 4 °C warming by the end of the century (assuming an average climate sensitivity of 3 °C) (Fischer et al., 2007a,b; Van Vuuren et al., 2008). This scenario is expected to lead to a relatively high need for adaptation. The mitigation scenario (2 °C) is based on stringent climate policy, consistent with the EU climate target. This scenario requires considerable mitigation action, but will also still lead to climate impacts, and thus need for adaptation. The scenario compares well to the scenario published by van Vuuren et al. (2010) and described there in detail.

For these two emissions scenarios, IMAGE has also calculated the expected changes across the globe in mean monthly temperature and rainfall (see Section 2.3). These climate scenarios were used to simulate changes in river flows across the global domain. Changes in exposure to water resources stress are calculated from the changes in river flows, and differences in impact between different emissions scenarios assessed. The analysis uses a number of climate models to represent the spatial variability in changes in temperature and rainfall, and two indicators of exposure to water resources stress.

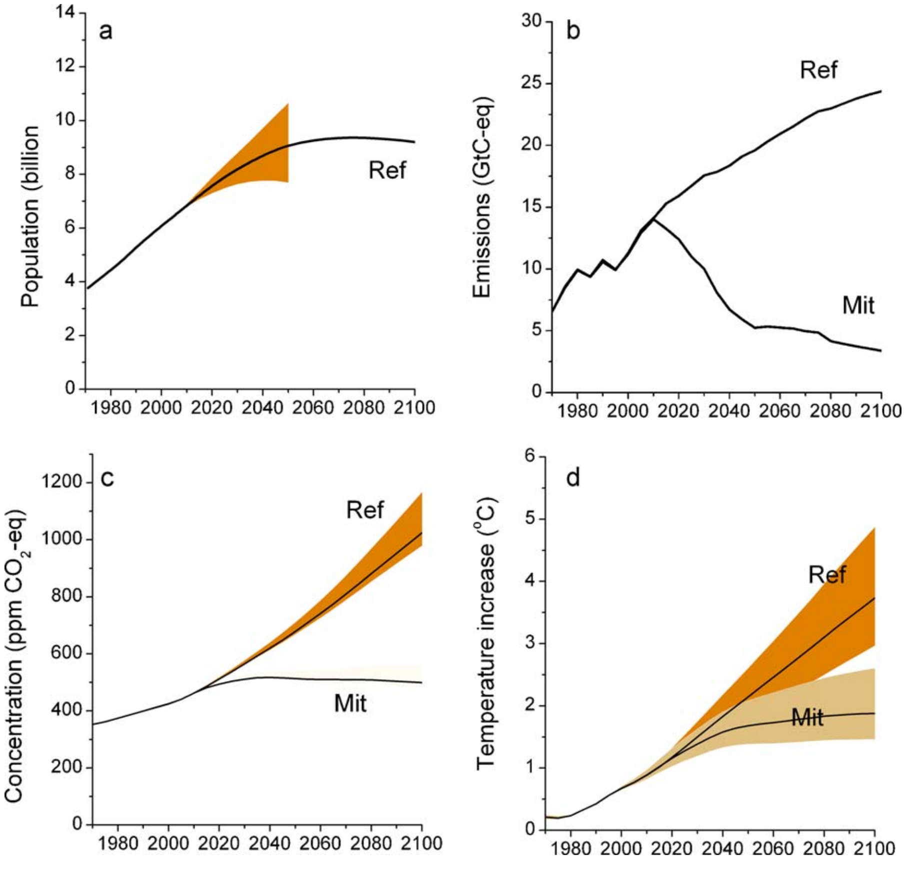

Fig. 1. The ADAM scenarios (a) population, (b) emissions and (c) CO_{2e} concentrations, and (d) temperature. The range in panel a shows the range between the UN low and high population projections, and the ranges in panel c and d represent uncertainty in carbon cycle and climate sensitivity based on Van Vuuren et al. (2008)).

2.2. Socio-economic and emission scenarios

2.2.1. Reference scenario

Greenhouse gas emission scenarios that explore events in the absence of climate policy are typically developed for two different purposes: (1) to explore the range of possible future developments and (2) to act as a reference to explore the consequences of alternative pathways (mostly mitigation scenarios). The SRES scenarios (Nakicenovic et al., 2000) form a well-known example of the first category. The study here falls in the second category. Typically, in these studies only one (medium) reference scenario is used as the focus lies on differences between the alternative pathways (based on explicit climate policy) and the reference scenario and not on the uncertainty in baseline developments. The same argument applies here. The reference scenario has been designed to follow medium assumptions for parameters like population, economic growth and emissions, using the IMAGE integrated assessment model to ensure consistency among the trends in these areas. The scenario is described in more detail elsewhere (van Vuuren et al., 2010).

For population projections, the scenario is based on the medium projection of the World Population Projections (UN, 2005) up to 2050 and the UN's long-range medium projections up to 2100 (Table 1, Fig. 1a). Under this projection, global population steadily increases to almost 9.1 billion people by 2050, levels off and reaches a level just below 9 billion in 2100. This projection is, to 2050, consistent with the latest UN population projections (UN, 2008). The population scenarios are downscaled by using the national population trends included in the UN projections, and using a linear downscaling algorithm to downscale to a 0.5° × 0.5° grid (see Van Vuuren et al., 2007). For economic growth, the scenario follows projections made by Cambridge University for the period up to 2050, which have been extended up to 2100 on the basis of the B2 scenario (van Vuuren et al., 2010). The scenario can be characterized as a medium to high economic growth scenario (cf. Fischer et al., 2007a,b). Driven by these population and economic trends, world energy consumption more than doubles in the 2000–2050 period and increases by another 25% in the 2050–2100 period. Energy supply remains dominated by fossil fuels. Whilst oil and natural gas production peak and subsequently decline (including unconventional resources), the use of coal increases during the whole scenario period.

The trends described above imply that emissions of carbon dioxide from fossil fuel combustion more than double until 2050 (Fig. 1b), and rise by a third again between 2050 and 2100 (consistent with a medium position within the literature range (Fischer et al., 2007a,b)). Land-use-related emissions of other greenhouse gases than carbon dioxide (in particular methane) increase steadily in the period 2000 to 2050 (driven by increasing agricultural production), but at a slower rate than energy related carbon dioxide. In the second half of the century, a stabilising population also leads to a stabilisation of agricultural emissions. Similarly, carbon dioxide emissions from land-use fall back to zero during the first half of the century. Atmospheric CO_2 concentrations exceed 1000 ppm CO_2e in 2100 (Fig. 1c).

Table 1
Continental population totals (millions) under the ADAM socio-economic scenario.

	2000	2020	2050	2080	2100
North America	309	367	429	447	453
South America	500	639	752	750	717
Africa	795	1204	1905	2298	2373
Europe	562	562	523	465	452
Asia	3720	4562	5187	5131	4946
Australasia	22	27	32	31	31
Global	5908	7361	8827	9122	8972

2.2.2. Mitigation scenario

The mitigation scenario aims at stabilising greenhouse gases at around 450 ppm CO_2e (Fig. 1c) and is similar to scenarios published elsewhere in the literature (Van Vuuren et al., 2007). The scenario allows an initial overshoot to about 510 ppm CO_2e (den Elzen and Van Vuuren, 2007). The scenario falls into the lowest scenario category based on its radiative forcing as defined in the Fourth Assessment Report (Fischer et al., 2007a,b). The emission reduction is achieved by using energy more efficiently, increased use of renewable and nuclear power, increased use of carbon capture and storage and reducing non-CO_2 emissions. As a result, global emissions peak around 2020, and reduce further with time (Fig. 1b). By 2050, emissions are reduced by more than 70% compared to the baseline and more than 80% by 2100. The consequences of the mitigation policies are not only obvious for energy, but also for global land use. Substantial land areas are used for afforestation and bio-energy.

2.3. Climate scenarios

The IMAGE model calculates the climate scenarios used to drive the hydrological model in two stages. First, global mean temperature change is determined based on the calculated greenhouse gas concentrations and the MAGICC-4 model (Wigley, 2003) using a climate sensitivity of 3.0 °C (some small changes were made to the original MAGICC code, especially for the ocean system as described by Eickhout et al. (2004)). The MAGICC model has been shown to represent the behaviour of complex climate models relatively well. Fig. 1d shows the simulated change in global mean temperature under the two scenarios, relative to pre-industrial. The Reference scenario produces a change in global average temperature of 3.7 °C by 2100, relative to pre-industrial (3.5 °C relative to 1961–1990). This is somewhat comparable to the results for the A1b-scenario in AR4 (IPCC, 2007). The Mitigation scenario produces a change of 1.9 °C relative to 2100 (1.7 °C relative to 1961–1990) which is much lower than the lowest of the IPCC scenarios looked at by complex climate models for AR4 (around 2.5 °C in 2100 for the B1 scenario – and still increasing at that time).

Second, spatial scenarios describing change in mean monthly temperature and precipitation in 2020, 2050, 2080 and 2100 under the Reference and Mitigation scenarios are calculated in IMAGE using a pattern-scaling approach with patterns derived from four climate models. The climate model patterns are linearly interpolated to the 0.5 × 0.5° scale on the basis of the global mean temperature increase (by using the change calculated in climate model runs and using this in combination with historical data). The effect of sulphate aerosols are incorporated using the method of Schlesinger et al. (2000). Pattern-scaling assumes a linear relationship between global mean temperature change and local temperature or precipitation change. The literature suggests that the method works relatively well for temperature, but for precipitation, results are less convincing (Cabré et al., 2010). It should be noted, however, that the geographical patterns of precipitation changes are very uncertain in any case; for this reason, the study uses multiple downscaled patterns that capture a wide uncertainty range. So far, scaling techniques have only been tested for scenarios with increasing emissions (e.g. Mitchell, 2003), but not for aggressive mitigation scenarios where emissions decline. The climate patterns used here are ECHAM4, CSIRO2, CGCM11 and HadCM2 (IPCC 2001). These climate patterns are now relatively old and were assessed in the IPCC's Third Assessment Report, but as they are used for pattern scaling purposes only they still give a broad indication of the range in spatial patterns of future climate change. The general patterns of temperature and precipitation change included in these scenarios fall within the ranges of the later models reviewed in the AR4, and do not obviously represent only a portion of the change space (IPCC, 2007).

The patterns of change in mean monthly temperature and precipitation are applied to the CRU TS3 (Mitchell & Jones, 2005) climate 1961–1990 baseline to construct perturbed 30-year time series of monthly temperature and precipitation for each $0.5^\circ \times 0.5^\circ$ grid cell. It is assumed that there is no change in net radiation, windspeed and relative humidity, used by the hydrological model to calculate potential evaporation, or in the number of days on which precipitation falls.

2.4. The hydrological model

River runoff is simulated across the global domain at a spatial resolution of $0.5^\circ \times 0.5^\circ$, using the global hydrological model MacPDM (Arnell, 1999; Gosling & Arnell, 2010). MacPDM operates at a daily time step, and simulates grid cell runoff through a water balance accounting approach. Daily precipitation is generated stochastically from monthly precipitation, assuming in this application a fixed coefficient of variation of daily rainfall of 1.5. The simulated daily rainfall is scaled to match the original monthly total. Precipitation falls as snow if temperature is below a defined threshold, and snow melts once temperature rises above another threshold. Potential evaporation is calculated from temperature, net radiation, windspeed and vapor pressure using the Penman–Monteith formula. The model generates "quickflow" from the portion of the grid cell that is saturated; this portion varies over time as grid cell average soil moisture storage content varies. "Slowflow" is generated by drainage from the soil moisture store. Total runoff from the grid cell is the sum of quickflow and slowflow. The analysis here uses average annual runoff, averaged over the 30 years of simulated daily runoff. This average annual runoff can be interpreted as the average annual amount of water available for use within a grid cell. The total water available within a watershed is calculated by summing average annual runoff from each grid cell within the watershed. In this analysis, the continents and large islands are divided into 1163 watersheds, with areas ranging from 1120 km^2 to 2.2 million km^2 (with a median around 50,000 km^2). Another 118 watersheds represent small islands.

Validation analyses (Gosling and Arnell, 2010) show that MacPDM reproduces well observed patterns of average annual runoff. However, MacPDM – in common with other global hydrological models -tends to overestimate river runoff in some dry regions, largely because it does not simulate the re-infiltration of runoff into dry river beds ("transmission loss"), and its subsequent evaporation.

The version of MacPDM as used in this analysis is slightly different to that used in Arnell (2004) and Arnell et al. (2002), in two main ways. First, it undertakes 20 simulations for each grid cell, rather than just the one in the earlier application, in order to reduce the effect of differences in stochastic realisations on simulated daily rainfall, and hence runoff. In practice, this has very little effect on simulated average annual runoff. Second, the current analysis uses CRU TS3 to define the baseline climate, rather than the earlier CRU TS1. Again, the differences are small.

2.5. Water resources impacts

The implications of climate change for water resources are represented using two measures of water resources stress.

- One is based on water availability per capita in a watershed, and is termed the "water stress indicator" (Rijsberman, 2006). This is a widely used measure of water resources pressures (Falkenmark et al., 1989; Arnell, 2004; Hayashi et al., 2010), and a threshold of 1000 m^3/capita/year is generally used to indicate a watershed exposed to water resources stress. The measure is simple to calculate and to apply in the future requires just projections of future population, but assumes that water resources pressures are a function of the numbers of people in a watershed only, not the amount of water that those people actually use.
- The second measure is based on the ratio of withdrawals of water in a watershed to the water available, frequently termed the "water resources vulnerability index" (Rijsberman, 2006). This is also a widely-used measure of pressures on water resources (e.g. Raskin et al., 1997; Alcamo et al., 2007; Hanasaki et al., 2008; Vörösmarty et al., 2000), and a threshold withdrawals-to-availability ratio of 0.4 is used to define watersheds with severe water stress.

This second measure accounts for variations in withdrawals across watersheds and therefore tends to highlight pressures in watersheds with large amounts of irrigation, but requires projections of future withdrawals when used to estimate future water resources pressures. These projections are sensitive not only to projections of future population change, but also to assumptions about changes in domestic, industrial and agricultural water use intensity. As an illustration, projections of global withdrawals made by Shen et al. (2008) for 2075 are 36% higher than those made by Alcamo et al. (2007), for effectively the same population assumption. The Alcamo et al. (2007) projections assume a stronger growth in domestic withdrawals, but these are more than offset by the considerably larger increase in agricultural withdrawals assumed by Shen et al. (2008). The current analysis uses the Shen et al. (2008) projections as the basis for projections of future water withdrawals under the ADAM socio-economic scenarios. Under these projections, irrigation withdrawals per m^2 of irrigated area remain constant (implying any effects of climate change are offset by efficiency gains), but irrigation area increases as a function of population growth so irrigation withdrawals increase. Watershed withdrawals in 2000, 2020, 2050 and 2080 are estimated by calculating watershed per capita withdrawals under the B2 scenario used by Shen et al, and rescaling using the ADAM watershed populations. Withdrawals for 2100 are estimated by rescaling the 2080 per-capita withdrawals by the 2100 watershed populations.

For both measures, average annual watershed runoff is used as the metric of resource availability, although in practice scarcity is most likely to be influenced by shortages of water in dry years or in certain times of the year. However, the threshold values used in the literature – 1000 m^3/capita/year or a withdrawals-to-availability ratio of 0.4 – are based on average annual runoff. Both measures characterise exposure to water resources stress rather than representing actual "hardship" caused by a real lack of water. In some watersheds, water management infrastructure will be in place to manage stresses; in others, local water resources stresses may arise due to differential access to water within an apparently well-watered watershed. Neither measure represents access to water, which is frequently determined more by economic, political, institutional and cultural factors than physical water availability. Other more complicated indicators of water resources stress have been developed (as reviewed by Rijsberman, 2006), but these require assumptions about future changes in a range of socio-economic characteristics so have not been used here.

The effect of climate change on exposure to water resources stress (as measured by either of the two stress measures) is represented by two sets of indices. The first set compares the numbers of people living within water-stressed watersheds by a given year, with and without climate change. Here, people either can be exposed to water stress that were not exposed before; or, the opposite, not be exposed to water stress any longer. The resulting numerical indicators of the effects of climate change are:

1a: The number of people in a region who live in non-stressed watersheds that become stressed due to climate change (i.e. runoff decreases so that resources per capita fall below 1000 m^3/capita/year, or the ratio of withdrawals to resources rises above 0.4.)

1b: The number of people in a region who live in water-stressed watersheds that *move out of the stressed* category because of climate change (i.e. runoff increases so that resources per capita exceed 1000 m^3/capita/year, or the ratio of withdrawals to resources falls below 0.4.)

The second set of indices focuses on the people who live in water-stressed watersheds which *remain stressed* under climate change. Here, the level of water stress can increase or decrease. The two derived numerical indicators are:

1a: The number of people in a region living in water-stressed watersheds with a "significant" decrease in runoff.

1b: The number of people in a region living in water-stressed watersheds with a "significant" increase in runoff (but who still remain water-stressed.)

A "significant" change in runoff is defined to be greater than the standard deviation of average annual runoff due to natural multi-decadal climatic variability. This standard deviation was calculated by calculating multiple estimates of the 30-year average annual runoff using climate scenarios constructed from a long unforced simulation with the HadCM3 climate change pattern (Arnell, 2003): it typically ranges between 5 and 15%, with higher values in drier environments.

The overall effect of climate change on exposure to water resources stress (for each of the two stress measures) is summarised by summing 1a and 2a to characterise "population exposed to a potential increase in water resources stress due to climate change" and summing 1b and 2b to characterise "population with a potential reduction in water resources stress due to climate change". At first sight, one could calculate the net impact of climate change on water stress by summing up all numbers (1a + 2a − 1b − 2b). However, there are two reasons why this may not be appropriate.

First, in a water-stressed catchment, the challenges imposed by a given reduction in water availability could be greater than the benefits realised by the same proportionate increase in water availability. It may not be possible to store the extra water through a dry season, or the extra water may occur during flood events. The relative costs and benefits of decreases and increases in runoff will of course depend on local circumstances. Second, populations in water-stressed catchments with an increase in runoff cannot be set directly against populations in water-stressed catchments with a decrease in runoff, because these may be in completely different regions. A direct offset is only appropriate if surplus in one area can be directly be transferred to offset deficit in the other.

On this basis, it is more appropriate to present both numbers separately. Moreover, it is important to emphasize again (as for the underlying measures), that these aggregated indicators characterise exposure to the effects of climate change. They do not measure the actual impact of climate change, as measures may be in place or adaptations may be implemented which alleviate the effects of climate change.

3. Results

3.1. Populations exposed to water resources stress in the absence of climate change

Table 2 shows the number of people living in water-stressed watersheds, in the absence of climate change, through the 21st century, under both measures of water stress (water stress indicator and water resources vulnerability index). In 2000, approximately 1.6 billion people were living in watersheds with less than 1000 m^3/capita/year, equivalent to 27% of the world's population. Due to population change alone, these numbers increase to 2.8 billion (39%) in 2020 and 3.9 billion (43%) in 2100. In absolute terms these numbers are slightly lower than those in Arnell (2004) under the B2 population assumption. The majority of these people exposed to water stress live in South Asia and China, although by the end of the century close to a billion people in Africa live in watersheds with less than 1000 m^3/capita/

Table 2

Numbers of people living in water-stressed watersheds, in the absence of climate change (thus only accounting for population growth following the ADAM population projection).

(a) Water-stress indicator: water-stressed watersheds have average annual runoff less than 1000 m^3/capita/year										
	Millions					% of total population				
	2000	2020	2050	2080	2100	2000	2020	2050	2080	2100
North America	47	70	81	85	86	15	19	19	19	19
South America	25	38	58	57	54	5	6	8	8	8
Africa	150	288	699	885	946	19	24	37	39	40
Europe	129	133	106	97	95	23	24	20	21	21
Asia	1231	2253	2803	2851	2711	33	49	54	56	55
Australasia	0	0	0	0	0	0	0	0	0	0
Global	1581	2782	3747	3974	3892	27	38	42	44	43
(b)Water resources vulnerability indicator: water-stressed watersheds have withdrawals >40% of average annual runoff										
North America	130	196	274	300	304	42	53	64	67	67
South America	70	99	121	112	106	14	15	16	15	15
Africa	96	197	343	385	383	12	16	18	17	16
Europe	240	240	225	186	175	43	43	43	40	39
Asia	1835	2636	3201	3238	3107	49	58	62	63	63
Australasia	0	0	3	3	3	0	0	9	9	9
Global	2371	3367	4167	4224	4078	40	46	47	46	45

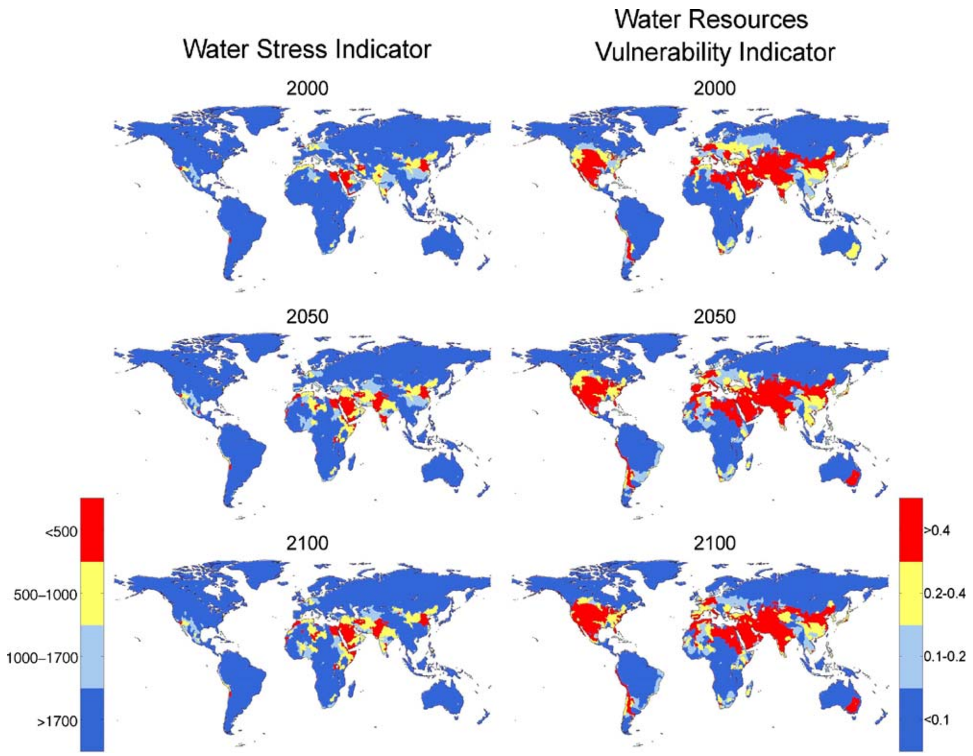

Fig. 2. Water resource stresses, in the absence of climate change, using two indicators of water resources stress.

year (Fig. 2a). Globally, in 2000 even more people live in water scarce areas on the basis of the second criterion (withdrawal-to-availability ratio greater than 0.4): 2.4 billion, or 40% of the world's population. The absolute difference between the people living in water stress, based on the two indicators used, is greatest in North America, Europe and Asia; here the estimates based on per-capita withdrawals – largely for irrigation – are higher (Fig. 2b). In Africa the withdrawal-to-availability ratio shows fewer people living in water-stressed watersheds than the water availability per capita indicator.

Table 2 also shows that, according to the withdrawal-to-availability indicator, there are–at least until 2050 – no people living in water-stressed watersheds in Australasia. This appears counter-intuitive, as it is well-known that Australia suffers from water scarcity, at least in some regions. The apparent lack of exposure to water resources scarcity in this analysis reflects two factors: the spatially-coarse scale of aggregation and the use of average annual runoff as the indicator of resource availability. Australia's population is highly concentrated, mostly in the eastern parts of the country with relatively high runoff, but even here, at the watershed scale, average annual resources per capita are high and well above the 1000 m^3/capita/year threshold. At finer spatial scales, resources per capita will likely be below the 1000 m^3/capita/year threshold. Australia's runoff resource also varies

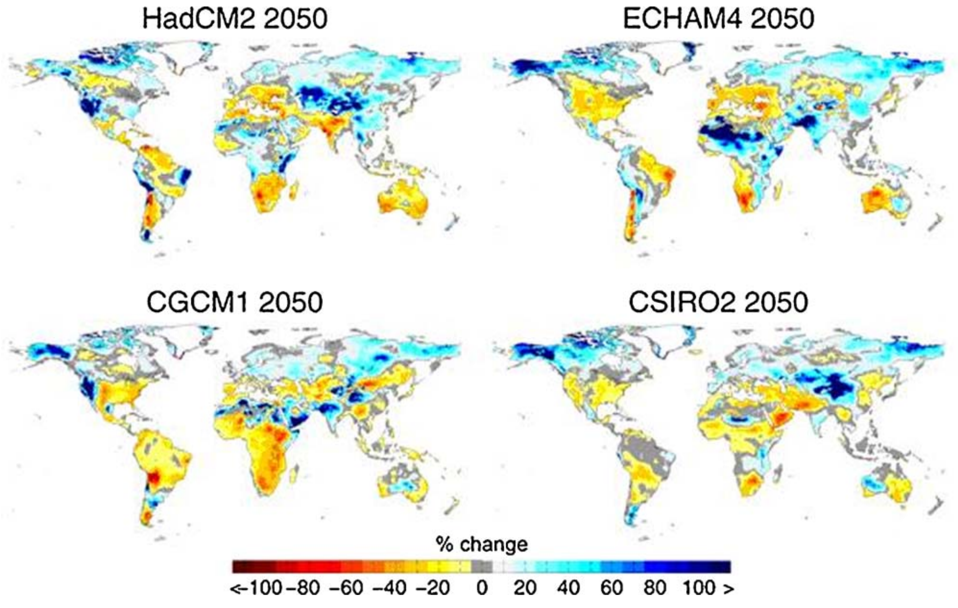

Fig. 3. Change in average annual runoff by 2050 (relative to 1961–1990) under the reference scenario.

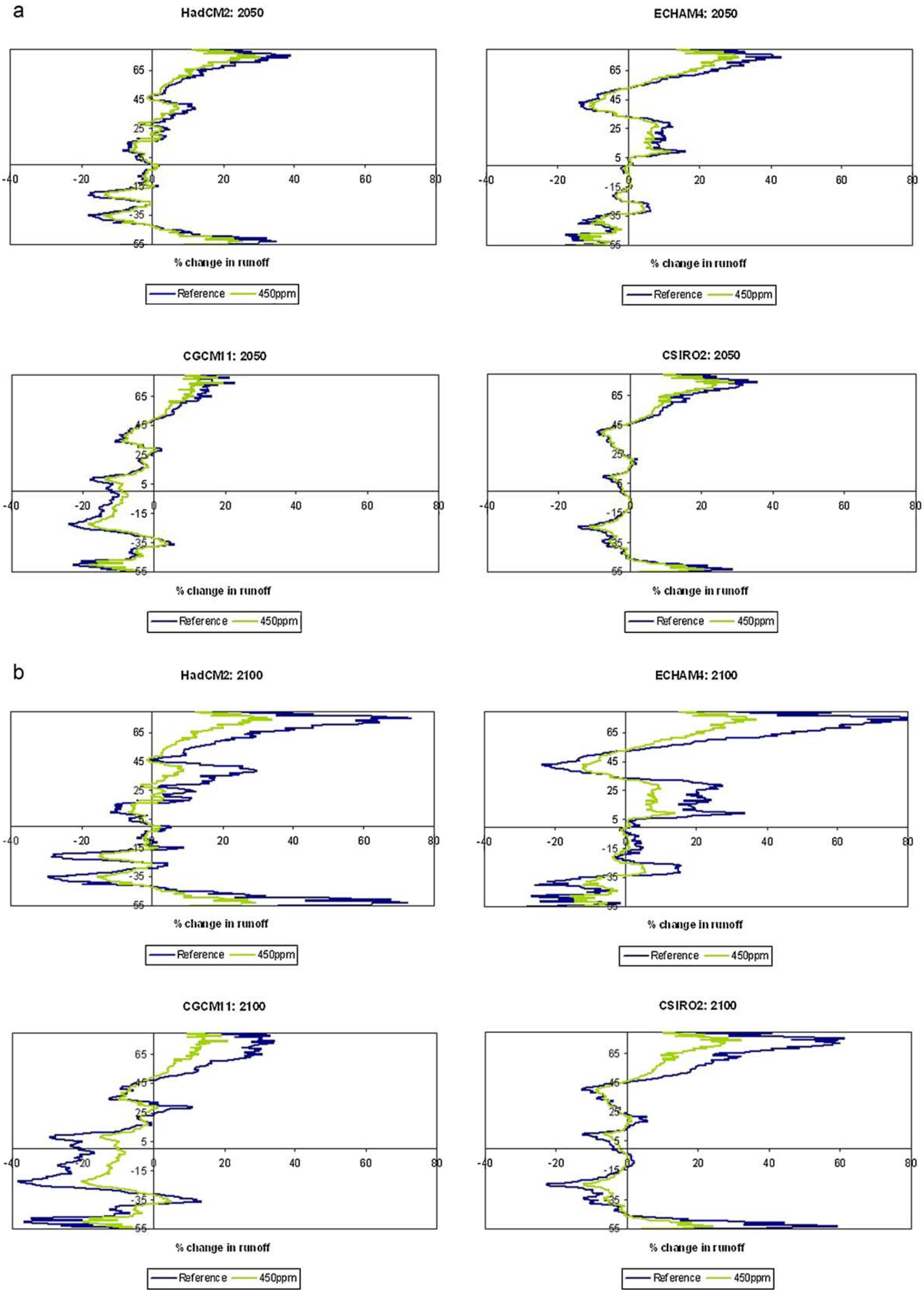

Fig. 4. Latitudinal change in runoff (relative to 1961–1990): 2050 (top), 2100 (bottom).

considerably from year to year, and in dry years even at the large watershed scale resources can be below the 1000 m^3/capita/year threshold. It is therefore possible that the indicators used in this analysis underestimate the actual exposure to water resources stress, because of the temporal and spatial scales at which they are calculated.

3.2. Hydrological consequences of climate policy

Fig. 3 shows the change in average annual runoff under the Reference scenario by 2050, for the four climate change patterns. The patterns of change are different from the patterns in other global-scale assessments (e.g. Arnell, 2003) because different

Table 3
Global numbers of people (millions) exposed to increase or decrease in water resources stress due to climate change.

		Increase in water resources stress				Decrease in water resources stress			
		2020	2050	2080	2100	2020	2050	2080	2100
(a) Water-stress indicator: water-stressed watersheds have less than 1000m^3/capita/year									
HadCM2	Reference	254	1528	1694	1674	100	790	1509	1698
	Mitigation	254	1358	1449	1249	100	703	719	784
CGCM11	Reference	259	959	1699	1960	64	1021	1294	1400
	Mitigation	260	793	1208	1362	64	886	947	939
CSIRO2	Reference	391	1393	1776	1948	169	278	665	691
	Mitigation	391	1179	1317	1434	169	144	129	136
ECHAM4	Reference	412	516	583	570	1841	2524	3017	2991
	Mitigation	225	475	471	454	740	1577	2608	3362
(b) Water resources vulnerability indicator: water-stressed watersheds have a ratio of withdrawals to resources of greater than 0.4									
HadCM2	Reference	294	1499	1640	1642	153	811	1435	1640
	Mitigation	291	1308	1421	1333	144	612	549	590
CGCM11	Reference	409	1019	1545	1780	23	1100	1381	1618
	Mitigation	407	801	932	946	23	960	1009	1007
CSIRO2	Reference	475	1382	1739	1683	147	414	846	841
	Mitigation	471	1297	1415	1421	138	280	283	318
ECHAM4	Reference	387	775	934	949	617	2511	2802	2762
	Mitigation	387	736	766	730	617	1437	2261	2355

climate models are used, but the patterns in Fig. 3 are within the range of uncertainty in other studies. Whilst there is some consistency at high latitudes, southern Africa and the eastern Mediterranean, there is more difference between the patterns in other parts of the world. Three of the patterns project substantial increases in runoff across much of south Asia, for example, whilst the other projects a large decrease. Two of the patterns project increases in runoff across much of China; two project decreases.

Fig. 4 summarises the relative changes under the Reference and Mitigation scenarios in 2050 and 2100, by plotting the change in latitudinal average runoff. Clearly, the latitudinal average runoff hides considerable longitudinal variations (see HadCM2 at about 45°N north in Fig. 3), but the plots do give an indication of the relative effect of the Mitigation scenario on changes in runoff. By the 2050s, the difference between the Mitigation scenario and the Reference scenario is relatively small. This is due to inertia in the

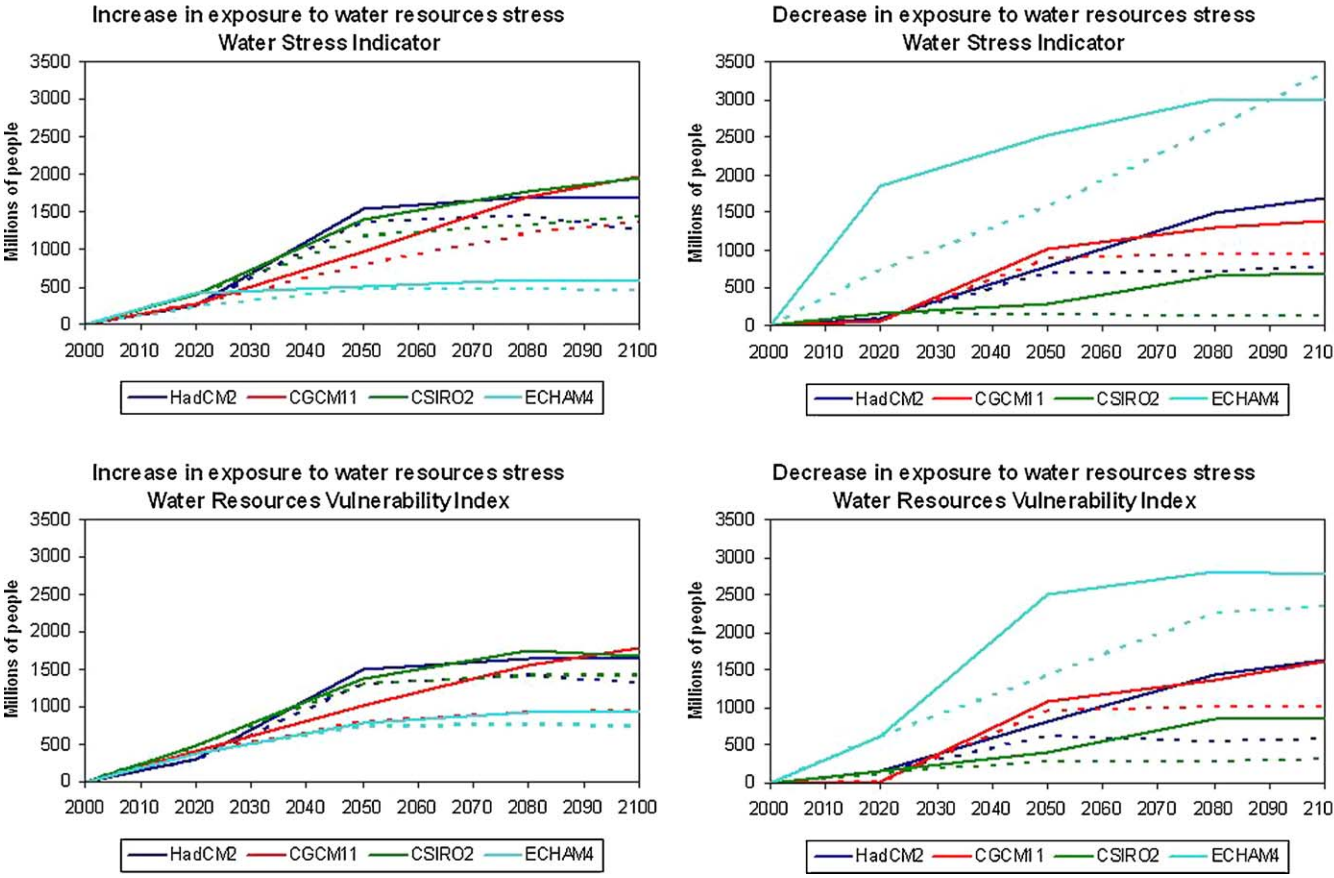

Fig. 5. Increase and decrease in global exposure to water resources stress due to climate change through the 21st century. Reference scenario (solid) and Mitigation scenario (dotted). (a) Water stress indicator and (b) water resources vulnerability index.

climate system, but also due to the reduction in sulphur emissions induced by the climate policy (that partly offsets the gains from the reductions in greenhouse gas emissions). The difference is more apparent at 2100 where the Mitigation scenario typically results in approximately half of the change under the Reference scenario. By 2050, the Mitigation scenario typically avoids between 16 and 30% of the change in runoff under the Reference scenario, and by 2100 mitigation avoids between 43 and 65%. The range increases between 2050 and 2100 because the differences in pattern between the four climate models increase. Note that although the patterns of absolute change in runoff vary between the four climate model patterns, the *percentage* of changes in runoff avoided by the Mitigation scenario is very consistent across the four models.

At one level, this is to be anticipated because in each case the Mitigation scenario represents a fixed proportion of the changes in the Reference scenario. However, this does not result in the same ratio difference in change in runoff. Simply rescaling the Reference scenario runoff changes (rather than rescaling the input scenario) would tend to overestimate increases in runoff, and underestimate decreases in runoff, under the Mitigation scenario. This is primarily because of the non-linear relationship between precipitation and runoff (a 20% increase in rainfall does not necessarily produce twice the change in runoff as a 10% increase in rainfall), and partly because of the differing relative importance of changes in precipitation and evaporation with different changes in mean temperature. This latter effect varies between the climate models with their different patterns of change in precipitation and evaporation.

3.3. Implications for water resources

Table 3 summarises the impacts of the Reference and Mitigation scenarios on global exposure to water resources stress, for the four climate model patterns, for the two measures of water resources stress (resources per capita (Table 3a) and the ratio of withdrawals to resources (Table 3b)) (results by continent are given in online supplementary material). Results are shown for the sum of the numbers of people in watersheds moving into/out of water stress and people living in water-stressed watersheds with an increase/decrease in stress (1a + 2a and 1b + 2b). The largest contribution to the total comes, in most cases, from the numbers of people already living in water-stressed watersheds who are exposed to either a decrease or an increase in runoff. The numbers for the Reference

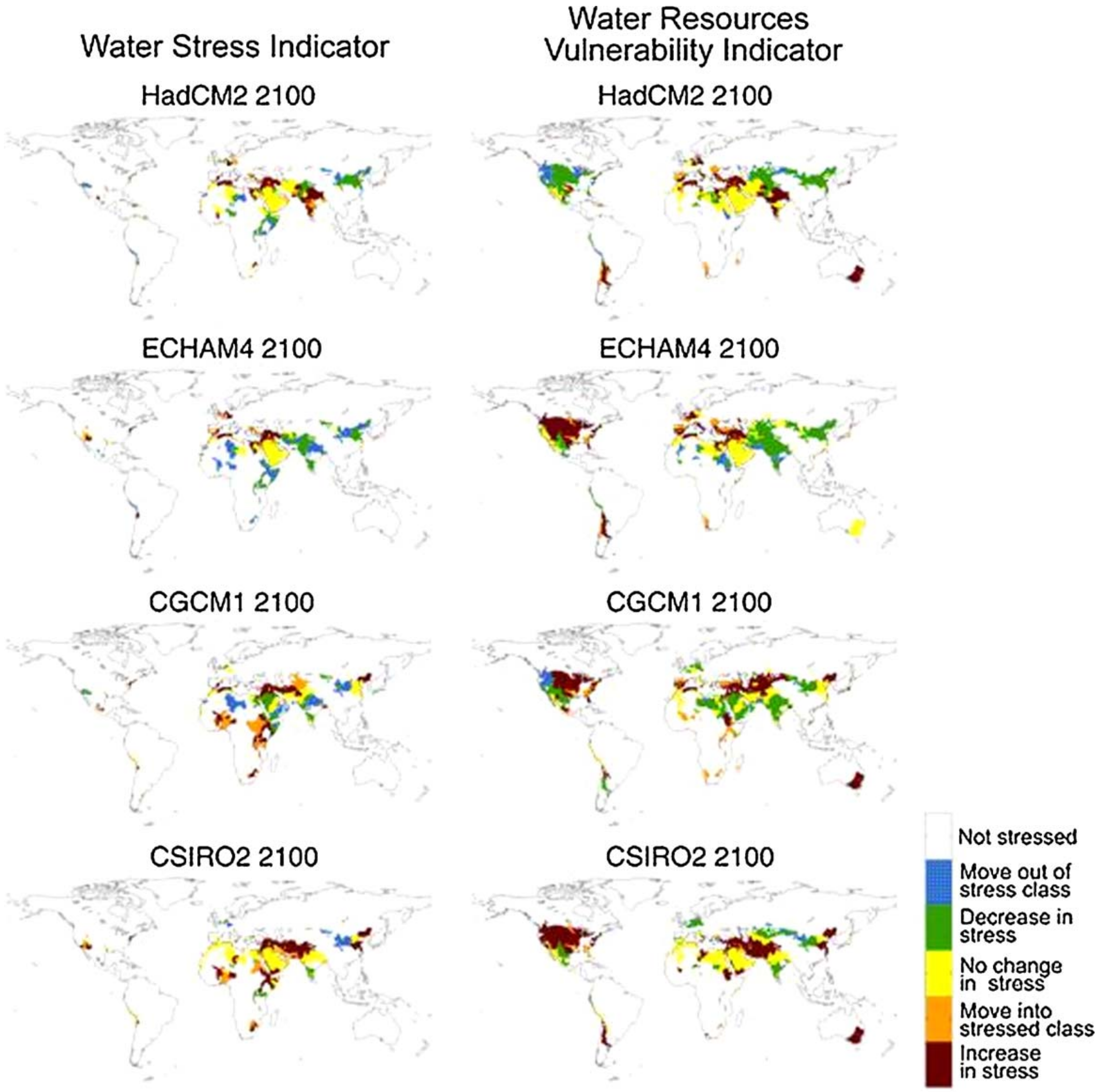

Fig. 6. Effect of climate change on exposure to water resources stress in 2100, for two stress measures, and four climate models: Reference emissions scenario. (a) Water stress indicator and (b) water resources vulnerability index.

scenario in Table 3 cannot be compared directly to those from other studies using similar impact metrics (e.g. Arnell, 2004), partly because the population data are different and partly because different climate model patterns are used. The orders of magnitude are, however, similar.

Fig. 5 plots the effect of climate change on exposure to water resources stress through the 21st century, at the global scale, under the four climate patterns and the Reference and Mitigation scenarios. Note that it is not appropriate to compare all combinations of Reference and Mitigation scenarios in Fig. 5; it is only appropriate to compare pairs from the same climate model pattern.

From these results, it is possible to draw a number of conclusions. First, the potential magnitude of the effect of unmitigated climate change on water stress is large. By the end of the 21st century, unmitigated climate change (4 °C warming) may lead to *increased* exposure to water resources stress for between 6 and 22% of the global population, using resources per capita as the indicator, and between 11 and 18% of global population using the ratio of withdrawals to availability ratio as the indicator of stress. Unmitigated climate change would also lead to apparent *reductions* in exposure to stress for between 8 and 33% of the global population (9–31% with the water resources vulnerability index) largely due to projected increases in rainfall in populous regions of south and north east Asia, but as argued in Section 2 – these two sets of figures should not be summed. It should be noted that the latter number is larger than the former.

Second, there is considerable variation in the absolute estimated impact between the four climate patterns used in this analysis. This variation is almost entirely driven by variation in the spatial pattern of change in runoff as simulated under the four patterns (Fig. 3 and Fig. 6), and is illustrated further in Fig. 7. At the global scale, the ECHAM4 pattern implies a rather smaller increase in exposure to stress than the other three patterns, and a larger apparent decrease in exposure (indeed, with ECHAM4 it appears that by 2100 mitigated climate change has a greater "beneficial" effect on populations exposed to water stress than unmitigated climate change, even though the change in rainfall and temperature is smaller: this reflects the complex balance between changes in rainfall and evaporation in some catchments). The two patterns which project reductions in runoff across parts of south Asia – HadCM2 and CSIRO2 – project the largest increase in exposure to water resources stress in Asia, and conversely the two patterns which project substantial increases in runoff across South Asia – ECHAM4 and CGCM1 – produce large apparent reductions in exposure to water resources stress.

Third, the Mitigation scenario avoids only a proportion of the impacts projected under the Reference scenario. This is illustrated in Fig. 8, which shows the percentage of the impacts under the Reference scenario avoided by the Mitigation scenario, by continent, climate change pattern and measure of water resources stress. In the short term (2020) avoided impacts are small. In 2050, the Mitigation policy avoids between 8 and 17% of the increased exposure to water resources stress (5–21% using the ratio of withdrawals to resources). In later years differences become much more substantial: between 15 and 29% in 2080 (13–40%), and between 20 and 31% (15–47%) in 2100. These proportions depend to a certain extent on the indicator of exposure to climate change. Proportions of impacts avoided tend to be larger when indicator 1a (numbers of people living in watersheds which become stressed) is

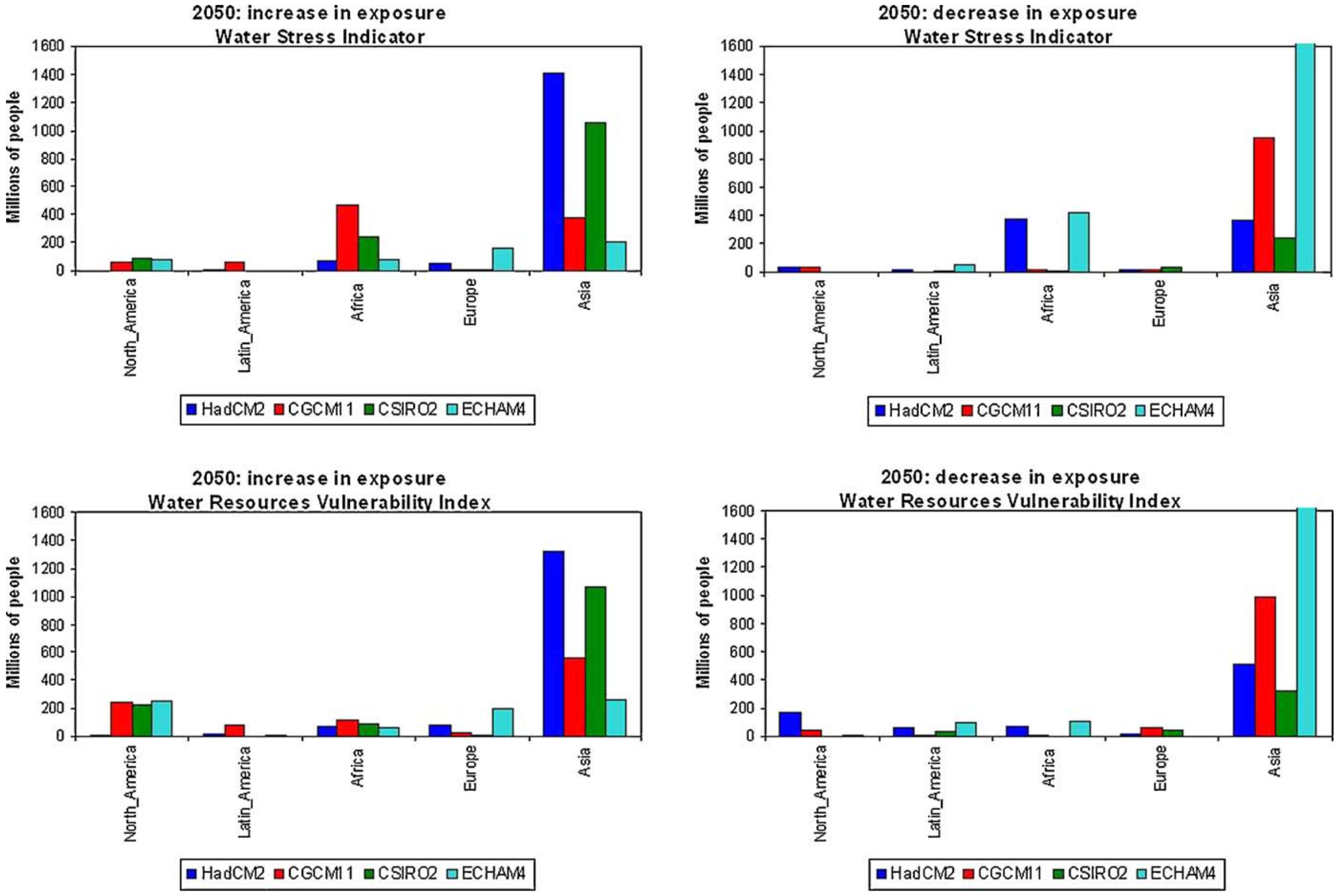

Fig. 7. Increase and decrease in continental exposure to water resources stress in 2050 (Reference scenario), by continent, with the four climate model patterns. (a) Water stress indicator and (b) water resources vulnerability index.

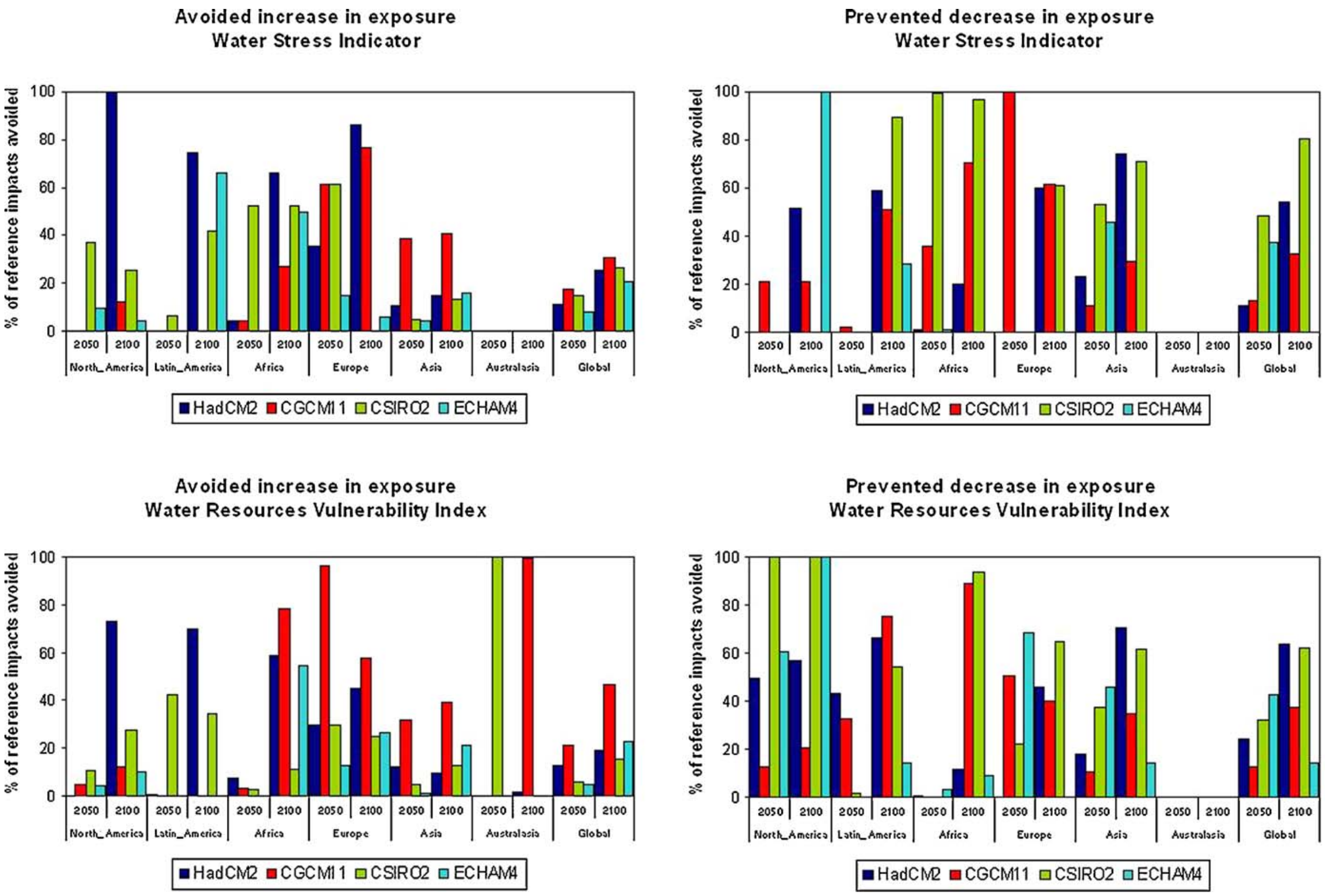

Fig. 8. Percentage of impacts avoided by the Mitigation scenario in 2050 and 2100. (a) Water stress indicator and (b) water resources vulnerability index.

used, rather than indicators 2a (numbers of people in stressed watersheds where runoff decreases) or 1a + 2a (the total numbers of people exposed to increase in water resources stress). The proportions of impacts avoided by climate policy are more consistent than the absolute avoided impacts, but there are differences between the four climate patterns. The greatest percentage effect of policy occurs with the CGCM1 climate change pattern, primarily because under this scenario a few watersheds are only just in the "increase in stress due to climate change" category. There is considerable variability in avoided impacts between continents, for a given climate model pattern, reflecting how close watersheds are to a change threshold. The percentage of impacts avoided does not necessarily increase with time through the 21st century. In Europe, for example, under CSIRO2, 61% of impacts are avoided in 2050, but by 2080 and 2100 climate policy avoids no impacts; the same watersheds are adversely affected under both the Reference and the mitigated climates.

4. Conclusions

This analysis has investigated the potential effect of climate policy on the impacts of climate change on exposure to water resources stress. Two different stress indicators were used, with four different climate patterns. The results show that according to the per-capita availability criterion the Mitigation policy assessed here (which aims to keep global average temperature change around 2 °C above pre-industrial temperature) reduces the population exposed to water stress by between 8 and 17% of the increase in exposure to water resources stress due to climate change by 2050. For 2080 and 2100, these numbers are 15–29% and between 20 and 31%, respectively. Using a second water stress indicator, the Mitigation policy avoids between 5 and 21% of impacts in 2050, 13–40% in 2080 and 15–47% in 2100. Thus, this relatively stringent climate policy appears to prevent well under half of the potential impacts of climate change, with little effect before the middle of the 21st century. The relative effect of climate policy varies strongly across the globe, since the exposure to water resources stress is sensitive to climate change by different degrees in different places. This geographical variation in sensitivity to climate change means the estimated absolute avoided impacts are dependent on the assumed spatial pattern of climate change. Since there is a high degree of uncertainty in the spatial pattern of climate change the absolute avoided impacts are inherently uncertain (and it is likely that adding extra climate change patterns would increase the range in estimated avoided impacts). However, across the global scale there is reasonable agreement between scenarios based on the different climate patterns on the percentage of change of runoff avoided globally by the Mitigation scenario.

A second point to note is that as well as avoiding increase in exposure to water stress, the Mitigation policy scenario also avoids the decrease in exposure water stress occurring in other areas as a result of climate change. As this concerns different people and different countries, there are ethical issues related to directly comparing these numbers (here, the different numbers are both presented – but have not been added).

There are a number of caveats around the conclusions. First, the quantitative assessments of change in exposure to water resources stress are strongly influenced by the particular climate models used to construct the climate scenarios, the assumptions involved in pattern scaling, hydrological model parameterisation and the scale of hydrological simulations. Second, the results are contingent on the assumed rate of population change; impacts and avoided impacts in a world with a more rapid rise in population, for example, would be quantitatively larger. Third, the results are influenced by the measure of exposure to water resources stress used, and by the assumed thresholds defining water stress. Finally, the indicators represent exposure to water resource stresses, rather than actual impacts or "hardship", as they do not incorporate the effects of current or future water management measures.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2011.01.015.

References

Alcamo, J., Florke, M., Märker, M., 2007. Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrological Sciences Journal 52 (2), 247–275.

Arnell, N.W., 1999. A simple water balance model for the simulation of streamflow over a large geographic domain. Journal of Hydrology 217, 314–335.

Arnell, N.W., 2003. Effects of IPCC SRES emissions scenarios on river runoff: a global perspective. Hydrology and Earth System Sciences 7, 619–641.

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change 14 (1), 31–52.

Arnell, N.W., Cannell, M.G.R., et al., 2002. The consequences of CO_2 stabilisation for the impacts of climate change. Climatic Change 53 (4), 413–446.

Bakkenes, M., Eickhout, B., et al., 2006. Impacts of different climate stabilisation scenarios on plant species in Europe. Global Environmental Change 16 (1), 19–28.

Bouwman, A.F., Kram, T., Klein Goldewijk, K. (Eds.), 2006. Integrated Modelling Of Global Environmental Change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency, Bilthoven.

Cabré, M.F., Solman, S.A., Nunez, M.N., 2010. Creating regional climate change scenarios over southern South America for the 2020s and 2050s using the pattern scaling technique: validity and limitations. Climatic change 98 (3), 449–469.

den Elzen, M.G.J., Van Vuuren, D.P., 2007. Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs. PNAS 104 (46), 17931–17936.

Eickhout, B., Den Elzen, M.G., Kreileman, G.J.J., 2004. The Atmosphere–Ocean System of IMAGE 2.2. RIVM report 481508017/2004. National Institute for Public Health and the Environment, Bilthoven.

Falkenmark, M., Lundquist, J., et al., 1989. Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. Natural Resources Forum 13, 258–267.

Fischer, G., Tubiello, F.N., et al., 2007a. Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080. Technological Forecasting and Social Change 74 (7), 1083–1107.

Fisher, B., Nakicenovic, N., et al., 2007b. Issues related to mitigation in the long-term context. In: Metz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L. (Eds.), Climate Change 2007 – Mitigation. Cambridge University Press, Cambridge.

Gosling, S.N., Arnell, N.W., 2010. Simulating current global river runoff with a global hydrological model: model revisions, validation and sensitivity analysis. Hydrological Processes In press.

Hanasaki, N., Kanae, S., et al., 2008. An integrated model for the assessment of global water resources. Part 2. Applications and assessments. Hydrology and Earth System Sciences 12 (4), 1027–1037.

Hayashi, A., Akimoto, K., et al., 2010. Evaluation of global warming impacts for different levels of stabilization as a step toward determination of the long-term stabilization target. Climatic Change 98, 87–112.

IPCC, 2007. In: Solomon, S., Qin, D., Manning, M. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 996.

Krol, M., Alcamo, J., et al., 1997. Global and regional impacts of stabilizing atmospheric CO_2. Mitigation and Adaptation Strategies for Global Change 1, 341–361.

Mitchell, T.D., 2003. Pattern scaling – an examination of the accuracy of the technique for describing future climates. Climatic Change 60, 217–242.

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25, 693–712.

Moss, R.H., Edmonds, J.A., et al., 2010. The next generation of scenarios for climate change research and assessment. Nature, doi:10.1038/nature08823.

Nakicenovic, N., et al., 2000. Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge UK.

Nicholls, R.J., Lowe, J.A., 2004. Benefits of mitigation of climate change for coastal areas. Global Environmental Change 14 (3), 229–244.

Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J.,Hanson, C.E. (Eds.), 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Raskin, P., Gleick, P., Kirshen, P., Pontius, G., Strzepek, K., 1997. Water Futures: Assessment of Long-Range Patterns and Prospects. Stockholm Environment Institute, Stockholm.

Rijsberman, F.R., 2006. Water scarcity: fact or fiction? Agricultural Water Management 80, 5–22.

Schlesinger, M.E., Malyshev, S., et al., 2000. Geographical distributions of temperature change for scenarios of greenhouse gas and sulphur dioxide emissions. Technological Forecasting and Social Change 65 (167–193.).

Shen, Y.J., Oki, T., et al., 2008. Projection of future world water resources under SRES scenarios: water withdrawal. Hydrological Sciences Journal 53 (1), 11–33.

Tubiello, F.N., Fischer, G.I., 2007. Reducing climate change impacts on agriculture: global and regional effects of mitigation, 2000–2080. Technological Forecasting and Social Change 74 (7), 1030–1056.

UN, 2005. World Population Prospects: The 2004 Revision. CD-ROM Edition–Extended Dataset. United Nations publications, Sales No. E.05.XIII.12, United Nations, Department of Economic and Social Affairs, Population Division.

UN, 2008. World Population Prospects: The 2008 Revision, Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, New York.

UNFCCC, 1992. United Nations Framework Convention on Climate Change http://www.unfccc.int/resources.

Van Vuuren, D.P., Den Elzen, M.G.J., Lucas, P.L., Eickhout, B., Strengers, B.J., Van Ruijven, B., Wonink, S., Van Houdt, R., 2007. Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. Climatic Change 81 (2), 119–159.

Van Vuuren, D.P., Meinshausen, M., Plattner, G.K., Joos, F., Strassmann, K.M., Smith, S.J., Wigley, T.M.L., Raper, S.C.B., Riahi, K., De La Chesnaye, F., Den Elzen, M.G.J., Fujino, J., Jiang, K., Nakicenovic, N., Paltsev, S., Reilly, J.M., 2008. Temperature increase of 21st century mitigation scenarios. Proceedings of the National Academy of Sciences of the United States of America 105 (40), 15258–15262.

van Vuuren, D.P., Isaac, M., Kundzewicz, Z.W., Arnell, N.W., Barker, T., Criqui, P., Bauer, N., Berkhout, F., Hilderink, H., Hinkel, J., Hof, A.F., Kitous, A., Kram, T., Mechler, R., Scrieciu, S., 2010. Scenarios as basis for assessment of mitigation and adaptation. Global Environmental Change in press.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.

Wigley, T.M.L., 2003. MAGICC/SCENGEN 4.1: Technical Manual. National Center for Atmospheric Research, Colorado USA.