

A global assessment of the impact of climate change on water scarcity

Simon N. Gosling · Nigel W. Arnell

Received: 31 January 2013 / Accepted: 18 July 2013 / Published online: 17 August 2013
© The Author(s) 2013. This article is published with open access at Springerlink.com

Abstract This paper presents a global scale assessment of the impact of climate change on water scarcity. Patterns of climate change from 21 Global Climate Models (GCMs) under four SRES scenarios are applied to a global hydrological model to estimate water resources across 1339 watersheds. The Water Crowding Index (WCI) and the Water Stress Index (WSI) are used to calculate exposure to increases and decreases in global water scarcity due to climate change. 1.6 (WCI) and 2.4 (WSI) billion people are estimated to be currently living within watersheds exposed to water scarcity. Using the WCI, by 2050 under the A1B scenario, 0.5 to 3.1 billion people are exposed to an increase in water scarcity due to climate change (range across 21 GCMs). This represents a higher upper-estimate than previous assessments because scenarios are constructed from a wider range of GCMs. A substantial proportion of the uncertainty in the global-scale effect of climate change on water scarcity is due to uncertainty in the estimates for South Asia and East Asia. Sensitivity to the WCI and WSI thresholds that define water scarcity can be comparable to the sensitivity to climate change pattern. More of the world will see an increase in exposure to water scarcity than a decrease due to climate change but this is not consistent across all climate change patterns. Additionally, investigation of the effects of a set of prescribed global mean temperature change scenarios show rapid increases in water scarcity due to climate change across many regions of the globe, up to 2 °C, followed by stabilisation to 4 °C.

1 Introduction

Water scarcity is a major global issue. Existing pressures on water resources will be exacerbated by increases in population and also by climate change. Various studies have explored how both these factors might affect global water scarcity in the future by using

This article is part of a Special Issue on “The QUEST-GSI Project” edited by Nigel Arnell.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-013-0853-x) contains supplementary material, which is available to authorized users.

S. N. Gosling (✉)

School of Geography, University of Nottingham, Nottingham NG7 2RD, UK
e-mail: simon.gosling@nottingham.ac.uk

N. W. Arnell

Walker Institute for Climate System Research, University of Reading, Reading RG6 6AR, UK

population projections and simulated changes in climate from global climate models (GCMs) with water resources models (Alcamo et al. 2007; Arnell 2004; Arnell et al. 2011; Gosling et al. 2010; Hayashi et al. 2010; Oki and Kanae 2006).

Most of this work acknowledges that projections of water scarcity are dependent upon not only scenarios of population change and emissions, but also the number of GCMs used for simulating the future climate. There are over 20 GCMs included in the Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007a), which all simulate different but plausible climates under identical emissions scenarios (Meehl et al. 2007b). Previous global assessments of the impact of climate change on water scarcity have used various numbers of CMIP3 GCMs ranging from one to six (Arnell 2004; Hayashi et al. 2010). Additional uncertainty can arise from the measure used to define water scarcity (Alcamo et al. 2007).

This paper presents the most comprehensive global-scale assessment to date of the impact of climate change on water scarcity. “Comprehensiveness” is interpreted as taking account of the various factors that affect climate change impacts assessment, including; the range of possible future climates projected by different GCMs, the different magnitudes of possible climate change due to different emissions trajectories, different population projections and water withdrawals, and differing methods for estimating water scarcity. To achieve this, we use climate change patterns from 21 CMIP3 GCMs, four socio-economic and emissions scenarios, and two different measures of water scarcity. We only use a single hydrological model, however, so we do not sample hydrological modelling uncertainty.

The overarching aim of the paper is to assess how our more comprehensive estimates of global water scarcity compare to previous assessments. Additionally, in light of The Copenhagen Accord and Durban Platform, which state ambitions of limiting the increase in global mean temperature to 2 °C and 1.5 °C above the pre-industrial value respectively, we assess how different amounts of global mean warming up to 4 °C might affect global water scarcity.

2 Methodology

2.1 Introduction

The experimental design involved applying the patterns of climate change from 21 GCMs to a global hydrological model to calculate average annual runoff, which in turn was used to estimate global water scarcity with a water resources model.

2.2 Climate change scenarios

Two types of scenarios are considered for each of the 21 GCMs; 1) four SRES emissions scenarios (B1, B2, A1B and A2) for three 30-year time horizons centred on 2020, 2050 and 2080; and 2) seven prescribed changes in global mean temperature relative to present (0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 4.0 °C of 30-year duration each). The current climate is characterised by the CRU TS3.1 data set (Harris et al. 2012) for the 1961–1990 time horizon, which is approximately 0.3 °C above pre-industrial.

Spatial and temporal climate change scenarios at $0.5^\circ \times 0.5^\circ$ resolution were constructed by pattern-scaling output from 21 CMIP3 GCMs (Meehl et al. 2007a) with ClimGen (Todd et al. 2011). ClimGen uses the change pattern for any given GCM to perturb a historical dataset (CRU TS3.1 in this study) to ensure minimal bias with respect to observations. This is often referred to as the delta method (Arnell and Gosling 2013). Further details on pattern-

scaling and the 21 GCMs we used are in Online Resource 1 in the Electronic Supplementary Materials (ESM) file. Not all 21 GCMs are independent of each other and they are considered equally plausible in this analysis. To help explore the effects of using different GCMs, we selected HadCM3 as an illustrative ‘marker’ GCM, which presents a plausible characterisation of the spatial variability of change in climate (Arnell et al. 2013).

2.3 The global hydrological model and water resources model

Simulations of average annual runoff across the global domain at a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$, for every climate change pattern and scenario, were performed with an established global hydrological model, Mac-PDM.09 (Gosling and Arnell 2011). Mac-PDM.09 is used in several recent studies (Arnell and Gosling 2013; Arnell et al. 2013; Hagemann et al. 2013; Thompson et al. 2013). Further details about Mac-PDM.09 are included in Online Resource 2.

The runoff simulations from Mac-PDM.09 were applied to a water resources model (Arnell et al. 2011; Gosling et al. 2010) to estimate water scarcity. For every climate change pattern we calculated two well-known measures of water scarcity (Rockström et al. 2009; Oki and Kanae 2006); 1) “Water Crowding Index” (WCI; a measure of the annual water resources per capita in a watershed) and 2) “The Water Stress Index” (WSI; a measure of the ratio of water withdrawals to resources). A WCI threshold of $<1,000 \text{ m}^3/\text{capita}/\text{year}$ and a WSI of >0.4 were used to indicate exposure to water scarcity (Rockström et al. 2009). For both measures, available water resource in each of 1339 watersheds across the globe was calculated by summing simulated average annual runoff from each $0.5^{\circ} \times 0.5^{\circ}$ grid cell within a given watershed. WCI is heavily dependent upon population size while the WSI accounts for variations in withdrawals across watersheds and therefore tends to highlight pressures in watersheds with large amounts of irrigation.

The water resources model calculates four metrics (Arnell et al. 2011) that isolate the *sole impact of future climate change* on water scarcity (i.e. they represent the *additional* impact of climate change *on top of* population and/or withdrawals pressure). This involves calculating first, future water scarcity in the *absence of climate change* (i.e. due to future population and/or withdrawals pressure only) and then subtracting this from the water scarcity that occurs due to the *combined* effects of future climate change *and* population and/or withdrawals pressure. The four metrics are:

- 1) The number of people in a region who live in watersheds *with no water scarcity in the absence of climate change* but that *enter water scarcity* due to climate change.
- 2) The number of people in a region who live in watersheds *with water scarcity in the absence of climate change* but that *move out of water scarcity* due to climate change.
- 3) The number of people in a region living in watersheds *with water scarcity in the absence of climate change* who see a “*significant*” *decrease in runoff* due to climate change.
- 4) The number of people in a region living in watersheds *with water scarcity in the absence of climate change* who see a “*significant*” *increase in runoff* due to climate change but who still remain in water scarcity.

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 was calculated from 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 and Gosling 2013).

For each of the two water scarcity measures, the impact of climate change on exposure to water scarcity (i.e. *on top of* future population and/or withdrawals pressure) is summarised by summing 1) and 3) to characterise population exposed to a potential increase in water scarcity due to climate change, and summing 2) and 4) to characterise population with a potential reduction in water scarcity due to climate change. Throughout the manuscript, for conciseness, these are referred to as an “increase in scarcity” and a “decrease in scarcity”, respectively, and the estimates for each can be considered as relative to the situation in the future (e.g. 2050) where there is higher population and withdrawals than present.

2.4 Socio-economic scenarios

When exploring water scarcity due to climate change under SRES scenarios, future population was taken from the IMAGE v2.3 representation of the B1, B2, A1B and A2 storylines (Van Vuuren et al. 2007) and used with the appropriate runoff simulations in the water scarcity model. When exploring the prescribed warming scenarios, future population was assumed to be equivalent to that under SRES A1B for the 30-year time horizon centred on 2050, because these climate projections are not associated with any specific time in the future or SRES scenario. Withdrawals were estimated by rescaling Shen et al.’s (2008) projections to match the population projections used here. Note that different projections of future withdrawals would give different indications of future water resources scarcity.

Watershed population exposure to water scarcity was aggregated to the national scale and then to the regional scale, so water scarcity can be expressed regionally in absolute (millions of people) and relative (as a percentage of regional population) terms. The countries included in each region are listed in Online Resource 3 and displayed in a map in Online Resource 4.

3 Results

3.1 Water scarcity in the absence of climate change

In the year 2000, depending on the measure of water scarcity, 1.6 (25 % of global population) and 2.4 billion (39 %) people are estimated to be living in watersheds exposed to water scarcity (Table 1). The greatest proportions of populations living in water-scarce watersheds are located in East Asia (660 and 666 million) and South Asia (491 and 1004). More people fall into the water scarcity category with the WSI than with the WCI (Table 1; see also Online Resource 5 for global maps). Notable regions where the two water scarcity measures result in opposing results (i.e. one measure results in water scarcity and the other measure does not), include parts of the US and Australasia.

Total global population in the years 2000, 2020, 2050 and 2080, under the A1B scenario, is estimated to be 6.1, 7.3, 8.2 and 7.8 billion respectively. This places pressures on future water resources and *in the absence of climate change* it is estimated that by 2050 under A1B, 3.1 (37 %) and 4.3 billion (53 %) people will be living in watersheds exposed to water scarcity, globally. The greatest absolute exposure to water scarcity is in South Asia (1.5 and 1.7 billion) and East Asia (0.7 and 1.2 billion).

3.2 Runoff changes

Simulated changes in average annual runoff by 2050 from Mac-PDM.09, when it is forced with the pattern of climate change from the HadCM3 GCM only under A1B, show runoff

Table 1 Numbers of people exposed to water scarcity in the absence of climate change (i.e. due to population change only), using two measures of water scarcity, for four time horizons, under the A1B scenario

		Millions				Percentage of population			
		2000	2020	2050	2080	2000	2020	2050	2080
a)	WCI (<1,000 m ³ /capita/year)								
1	North Africa	128	172	206	210	74	76	77	78
2	West Africa	7	19	42	42	3	5	9	9
3	Central Africa	0	0	5	6	0	0	3	3
4	East Africa	4	15	97	163	3	7	31	47
5	Southern Africa	16	10	11	12	9	5	5	5
6	South Asia	491	1273	1466	1292	34	69	70	67
7	South East Asia	0	0	0	0	0	0	0	0
8	East Asia	660	722	673	487	44	45	44	38
9	Central Asia	0	1	2	2	1	1	2	3
10	Australasia	0	0	0	0	0	0	0	0
11	Western Europe	112	115	160	164	29	29	38	39
12	Central Europe	7	7	6	5	5	5	5	5
13	Eastern Europe	4	5	5	5	2	2	2	3
14	Arabian Peninsula	34	76	143	190	73	92	98	99
15	Mashriq	27	48	92	93	21	28	45	48
16	Canada	5	6	7	7	17	17	17	17
17	US	34	58	76	79	12	17	19	19
18	Central America	21	48	53	50	13	22	21	20
19	Brasil	0	0	0	0	0	0	0	0
20	South America	4	5	18	19	2	2	7	7
21	Global	1555	2579	3064	2828	25	35	37	36
b)	WSI (>0.4)								
1	North Africa	98	182	230	234	56	80	86	87
2	West Africa	0	3	5	6	0	1	1	1
3	Central Africa	0	0	0	0	0	0	0	0
4	East Africa	0	12	57	69	0	5	18	20
5	Southern Africa	0	0	0	0	0	0	0	0
6	South Asia	1004	1419	1684	1559	70	77	81	81
7	South East Asia	1	23	75	70	0	4	10	11
8	East Asia	666	776	1231	1038	44	48	80	81
9	Central Asia	48	62	77	79	84	87	89	90
10	Australasia	0	0	3	3	0	0	6	6
11	Western Europe	205	197	216	238	53	49	51	57
12	Central Europe	36	33	30	7	28	26	26	7
13	Eastern Europe	22	24	24	21	10	11	12	12
14	Arabian Peninsula	40	82	144	191	86	99	99	99
15	Mashriq	72	117	144	142	55	67	70	73
16	Canada	7	8	10	10	22	22	25	25
17	US	124	158	233	258	44	47	58	62
18	Central America	55	82	95	90	32	38	38	36

Table 1 (continued)

		Millions				Percentage of population			
		2000	2020	2050	2080	2000	2020	2050	2080
19	Brasil	0	0	0	47	0	0	0	22
20	South America	15	30	55	84	8	14	21	30
21	Global	2393	3209	4314	4146	39	44	53	53

Please refer to Online Resource 3 and Online Resource 4 for details of the regional classification

increases relative to present (1961–1990) across large areas of East Asia (+30 %), South Asia (+30 %), the high northern latitudes (+40 %), and East Africa (+20 %) (see Online Resource 6(a)). Some areas see up to +90 % increases in runoff. Changes in runoff in South Asia and East Asia reflect large changes in climate on a large regional runoff volume seen in the present climate. Declines in runoff are simulated for Brasil (−60 %), South America (−30 %), Southern Africa (−40 %), Western Europe (−20 %) and Central Europe (−30 %).

In line with previous assessments (Gosling et al. 2010; Milly et al. 2005), there is high consistency that runoff decreases with climate change across central Europe and that it increases in the high northern latitudes but there is less agreement between all CMIP3 model climate change patterns across many regions of the globe, including parts of South Asia and East Asia (see Online Resource 6(b)). There is little change in the pattern of consistency when different time horizons (2020 and 2080) or scenarios (B1, B2, A2) are considered (not displayed).

3.3 Water scarcity due to climate change only under SRES scenarios

Regions of the globe experience both increases and decreases in water scarcity in the future due to the sole effects of climate change (see Fig. 1; expressed as a percentage of future regional population, and Online Resource 7; expressed in millions of people). We present the estimates associated with each climate change pattern and the range across the ensemble but we do not calculate any measures of central tendency because these can be an unreliable summary indicator of climate change impacts (Gosling et al. 2012). Tables that present the absolute and relative values displayed in Fig. 1 are presented in Online Resources 8–11). In Fig. 1, an increase in water scarcity of 100 % for a region would mean that in 2050, 100 % of the people living in watersheds in that region experience an increase in water scarcity that is attributable solely to climate change (i.e. the increase is not due to changes in population or withdrawals; it is additional to them). A number of general conclusions can be drawn from these results.

When considering all CMIP3 models together, a greater global population experience an increase in water scarcity due to climate change than a decrease, but this is not necessarily the case for individual models. In 2050 and under A1B, an increase in water scarcity is experienced globally by 0.5 to 3.1 billion (WCI) and 0.8 to 3.9 billion (WSI); a decrease is experienced by 0.2 to 2.2 and 0.1 to 2.7 billion for each water scarcity measure respectively. This is consistent across SRES scenarios as well as the two measures of water scarcity. However, this result does not hold for every individual CMIP3 model. For example, with the HadCM3 pattern more people are exposed to a decrease in scarcity (1.9 and 2.7 billion) than an increase (1.0 and 1.3) by 2050.

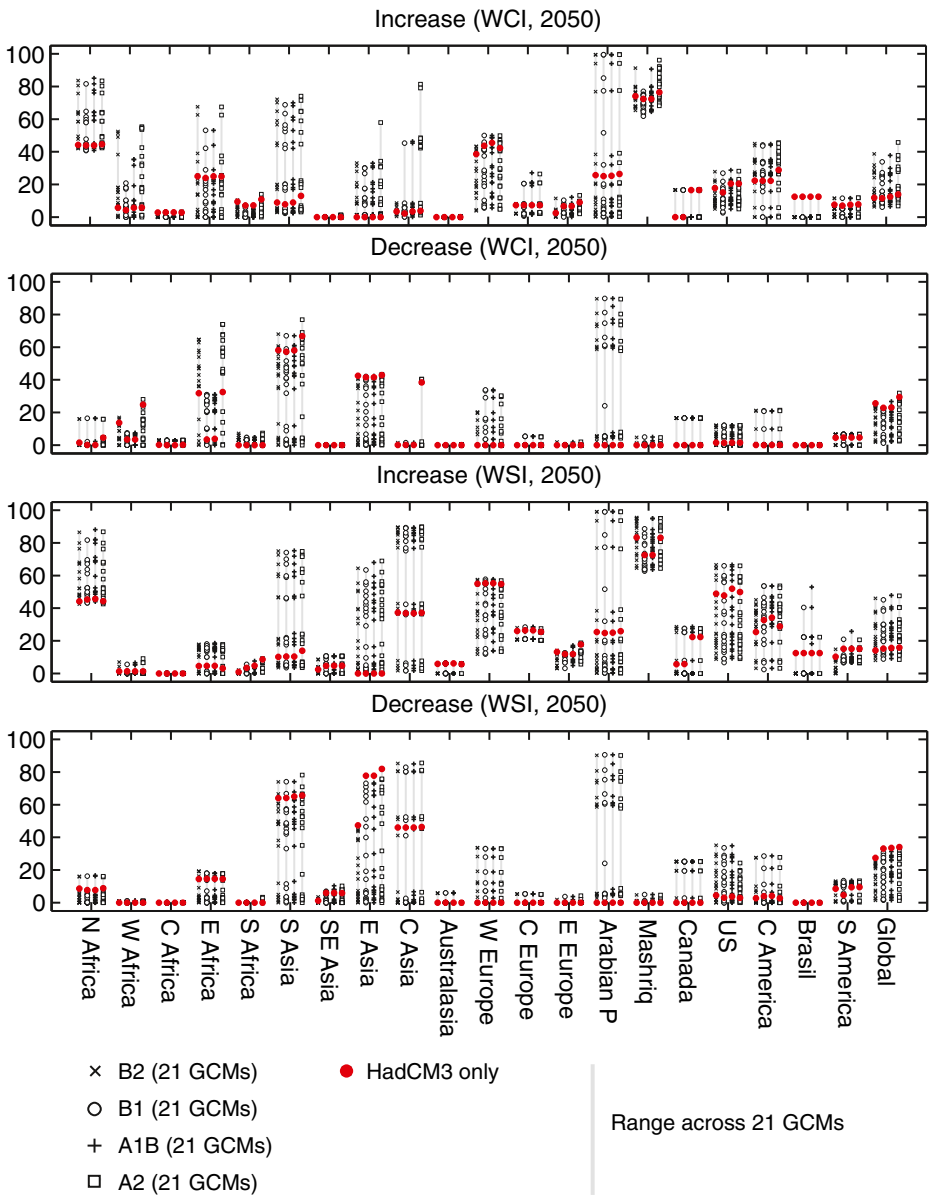


Fig. 1 Exposure to an increase and decrease in water scarcity attributable solely to climate change (i.e. the increases and decreases are additional to the effects of changes in future population or withdrawals), expressed as a percentage of future regional population, at 2050, using the WCI (1,000 m³/capita/year) and the WSI (0.4). The individual markers denote estimates for individual GCMs, with a different marker shape assigned to each SRES scenario. Filled red circles denote the HadCM3 GCM. The vertical grey bars denote the range across 21 GCMs

In absolute terms, uncertainty in the effects of climate change on water scarcity due to the application of all CMIP3 models is greatest for South Asia and East Asia. Here, by 2050 and under the A1B scenario, between 52–1460 million and 0–506 million people are exposed to increased water scarcity respectively, when using the WCI. If these two estimates are

expressed as a fraction of the total *global* population, then South Asia and East Asia account for 1–18 % and 0–6 % respectively of the global population exposed to increased water scarcity due to climate change. Thus a substantial proportion of the uncertainty in the global-scale effect of climate change on water scarcity is due to uncertainties in estimating the effects in South Asia and East Asia.

Close investigation of Fig. 2 explains why this uncertainty range is so large for South Asia and East Asia and also why it is greater for the WSI than the WCI. While the application of a single GCM (HadCM3) indicates that some watersheds in East Asia move out of water scarcity and/or see a decrease due to climate change, when using all CMIP3 models around 4–10/21 simulations indicate that water scarcity *increases* in these watersheds and around 11–14/21 show a decrease in scarcity. Climate change affects more watersheds in East Asia when using the WSI than the WCI, which means the uncertainty across simulations showing increases and decreases in water scarcity translate into a larger uncertainty range in absolute terms.

The differences in projections of water scarcity across the four scenarios are relatively small when compared with the differences across the 21 simulations. Globally, the absolute (relative) increases in scarcity by 2050 with HadCM3, when using the WCI are 1.0 (13 %), 1.0 (12 %), 1.1 (12 %) and 1.4 billion (14 %), for A1B, B1, B2 and A2 respectively. By comparison, the minimum and maximum values across the 21 simulations for absolute

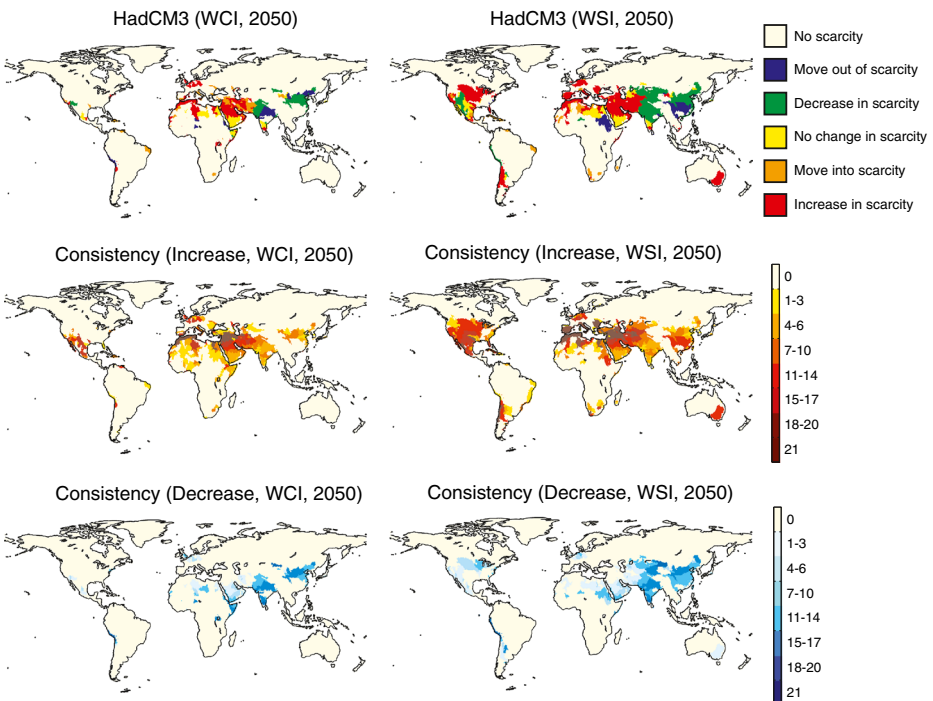


Fig. 2 The effect of climate change only on exposure to water scarcity in 2050 under the SRES A1B scenario, using the WCI (1,000 m³/capita/year; left panels) and the WSI (0.4; right panels). Top panels display the change in scarcity classes with the HadCM3 GCM only. The other panels show consistency across 21 simulations (with all CMIP3 models), in terms of the number of simulations out of 21 that show an increase in exposure (indicative of where there is an increase in scarcity or a watershed moves into water scarcity; middle panels), or decreases (a decrease in scarcity or move out of scarcity; bottom panels)

(relative) increases in scarcity by 2050 and using the same scarcity measure are 0.5 and 3.1 (6 and 38 %), 0.5 and 2.8 (6 and 34 %), 0.6 and 3.5 (6 and 39 %), and 0.7 and 4.7 billion (7 and 46 %) for A1B, B1, B2 and A2 respectively. This means that the range across the 21 simulations with all CMIP3 models for a single scenario (e.g. A1B) is greater than the range across all four emissions scenarios for a single GCM (HadCM3). This is observed at both the global-scale and at the regional-scale.

3.4 Sensitivity to the WCI and WSI thresholds for water scarcity

So far we have described exposure to water scarcity due to climate change based upon the two measures of water scarcity (WCI and WSI) with scarcity indicator thresholds of $<1,000 \text{ m}^3/\text{capita}/\text{year}$ and >0.4 respectively. A more rigorous analysis of the sensitivity of water scarcity exposure to the scarcity measure compares scarcity indicator thresholds (500, 1,000, $1,700 \text{ m}^3/\text{capita}/\text{year}$ and 0.1, 0.2, 0.4 respectively) (see Fig. 3 for relative exposure and Online Resource 12 for absolute exposure). These thresholds, which are arbitrary, have been used previously with the WCI for defining “extreme water shortage” (<500), “chronic water shortage” (<1000) and “moderate water shortage” (<1700) (Kummu et al. 2010; Arnell 2004) and with the WSI for defining “low stress” (>0.1), “medium stress” (>0.2) and “high stress” (>0.4) (Arnell 1999). This analysis demonstrates how sensitive estimates of water scarcity are to the selection of arbitrary thresholds.

The sensitivity of exposure to the three thresholds for each measure is appreciable. Generally, it is greater than sensitivity of exposure to SRES scenario but slightly less than sensitivity to climate change pattern. For example, the estimated increase in global exposure to water scarcity by 2050 under A1B and using the WCI ($1,000 \text{ m}^3/\text{capita}/\text{year}$) is 0.5 to 3.1 billion (6–38 %) across all CMIP3 models, while it is 0.5 to 1.5 billion (6–18 %) across the three WCI thresholds with HadCM3. This compares with 1.0 to 1.4 billion (12–14 %) across the four SRES scenarios with HadCM3. For some regions the sensitivity to indicator is comparable to sensitivity to climate change pattern (Central Asia and Central Europe).

3.5 Water scarcity due to climate change only under prescribed warming scenarios

Exposure to water scarcity, as measured with the WCI, increases non-linearly with global mean temperature and there are clear overlaps between the ranges for increases and decreases in exposure across CMIP3 models (as observed under the SRES scenarios) in relative (Fig. 4) and absolute (Online Resource 13) terms. Exposure to water scarcity increases steeply up to $2 \text{ }^\circ\text{C}$ in many regions (North Africa, East Africa, Mashriq, Arabian Peninsula and South Asia) and then stabilises by $4 \text{ }^\circ\text{C}$. This is because by this point all the watersheds that see a decrease in precipitation experience a significant decrease; beyond this point there are no further areas where precipitation decreases significantly. With a higher threshold for the definition of ‘significant’ change, the limit would obviously occur at a higher global mean temperature. Global exposure to an increase (decrease) in water scarcity with HadCM3 by 2050 and assuming A1B for 1, 2, 3 and $4 \text{ }^\circ\text{C}$ prescribed warming, is 760 (1807), 973 (1872), 1055 (1897) and 1161 (1905) million people respectively, but the uncertainty range across all CMIP3 models is considerable.

4 Discussion and conclusions

Our estimate of present-day populations living within watersheds exposed to water scarcity (1.6 and 2.4 billion) is consistent with other studies that have published estimates around 2.4

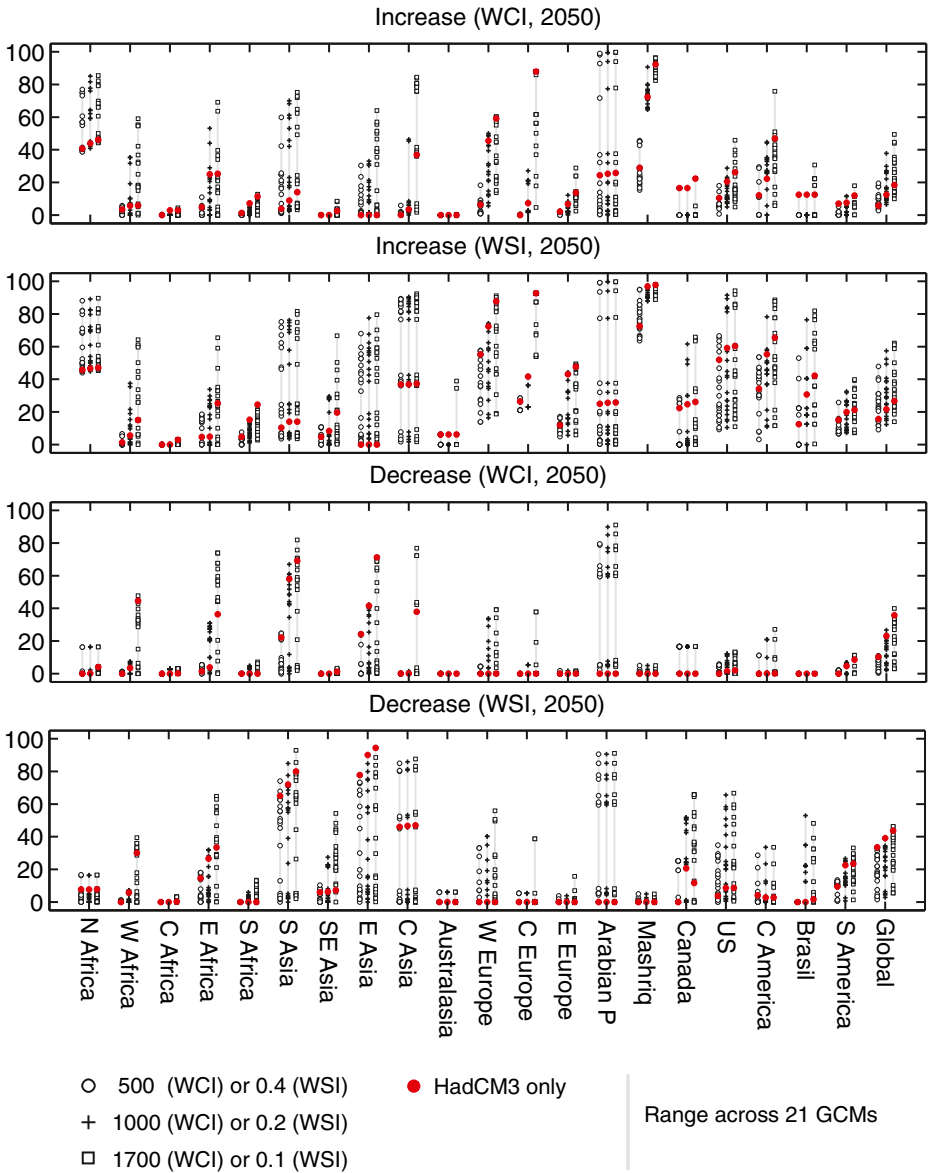


Fig. 3 Comparison of WCI and WSI water scarcity measure thresholds. Exposure to an increase or decrease in water scarcity due to climate change is expressed as a percentage of regional future population in 2050, assuming the A1B scenario

billion (Oki and Kanoe 2006), 1.4 and 2.2 billion (Arnell 2004), 1.7 and 2.3 billion (Revenga et al. 2000), 1.6 and 2.4 billion (Arnell et al. 2011), 1.2 billion (Hayashi et al. 2010), and 1.6 and 2.3 billion (Alcamo et al. 2007); the ranges are due to the application of different measures of water scarcity. By 2050, the effects of population increases alone mean that 3.1 and 4.3 billion people (37 and 53 %) will be living in watersheds exposed to water scarcity, which is similar to previous estimates around 3.4 and 5.6 billion (39 and 48 %) (Arnell

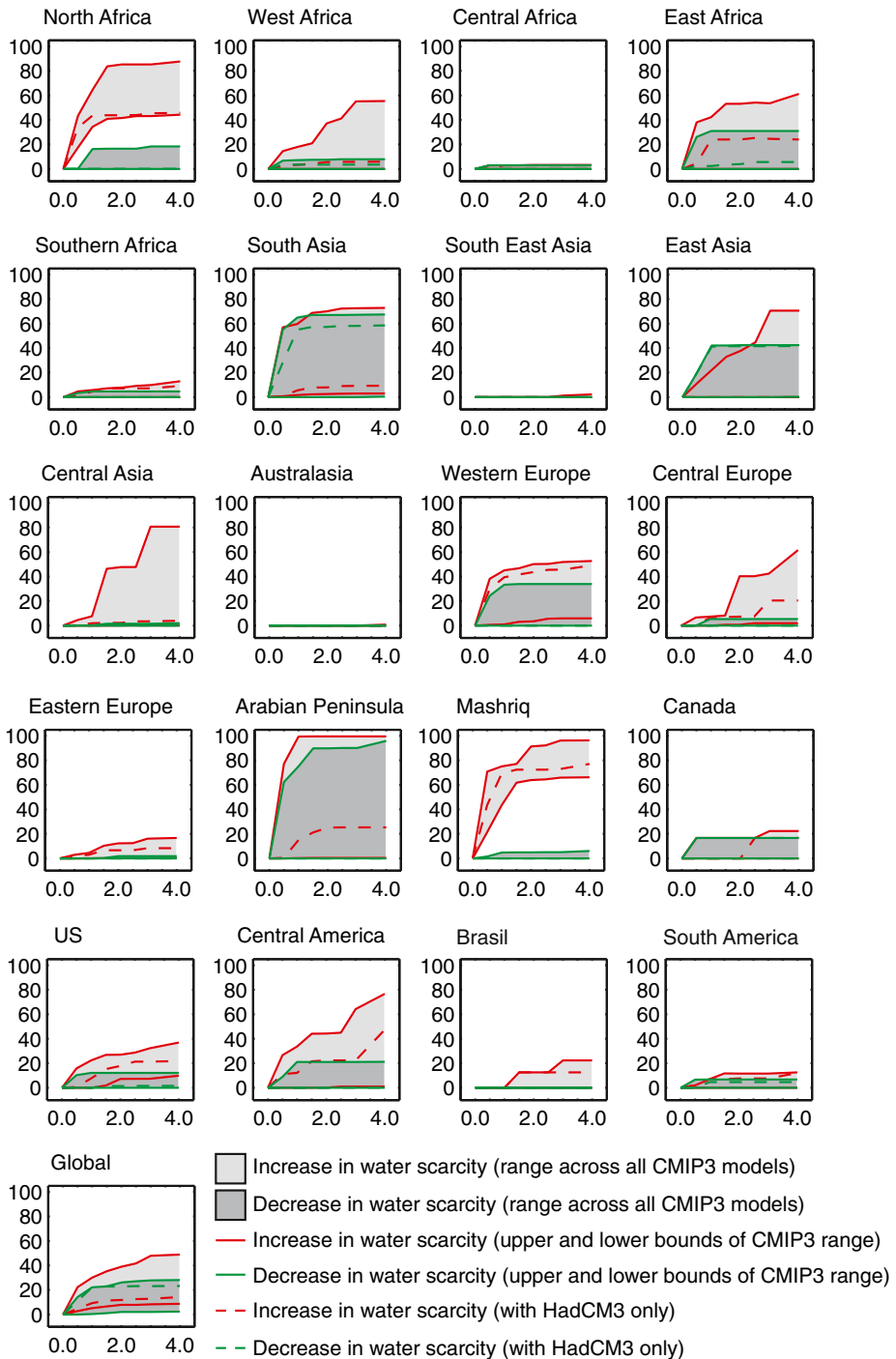


Fig. 4 Relationship between global temperature increase above 1961–1990 and exposure to water scarcity due to climate change, using the WCI. Expressed as a percentage of regional population, under an A1B socio-economic scenario in 2050

2004), 3.7 and 4.2 billion (42 and 47 %) (Arnell et al. 2011), and 3.8 billion (40 %) (Hayashi et al. 2010).

Direct comparisons of projected changes in exposure to water scarcity with other studies is not straightforward because of the application of different climate models, emissions and population scenarios, hydrological models, and measures of water scarcity. An additional issue that complicates inter-study comparisons is the spatial scale at which water scarcity is calculated. We estimated watershed population exposure to water scarcity and aggregated this to the national scale and then to the regional scale. Alternative approaches have conducted analyses at the scale of individual grid cells (Oki and Kanae 2006; Vörösmarty et al. 2000), countries (Oki et al. 2001) and food production units (Kummu et al. 2010). While the above comparisons do not account for these differences, a tentative comparison can be made, however, with two studies that both used a previous version of the hydrological model we applied and a WCI threshold of 1,000 m³/capita/year to define water scarcity at the watershed scale (then aggregating to country and regional scales). Arnell (2004) calculated a global increase in exposure (in billions of people) by 2055 under A2 of 1.1 to 2.8, across 6 GCMS. Our estimates by 2050 under A2 are 0.7 to 4.7, across 21 GCMS. Arnell et al. (2011) used a “Reference” scenario that is comparable to A1B and calculated a global increase in exposure by 2050 of 0.5 to 1.5 billion across 4 GCMS. Our estimate under A1B is 0.5 to 3.1 billion, across 21 GCMS.

Compared with these two studies, our estimates present a wider range that encapsulates both, but with very little difference at the lower-end and a considerable increase at the upper-end (over 1 billion people). This is because our assessment considered many more patterns of climate change from GCMs than either of the two studies. Some of the GCMs we used will simulate lower precipitation with climate change than those used by Arnell (2004) and Arnell et al. (2011). In absolute terms, uncertainty in the effects of climate change on water scarcity due to the application of all CMIP3 models is greatest for South Asia and East Asia, since these are two regions where GCMs show large differences in the magnitude, and sometimes sign, of precipitation change (Meehl et al. 2007b), and hence runoff change. Thus a substantial proportion of the uncertainty in the global-scale effect of climate change on water scarcity is due to uncertainties in estimating the effects in South Asia and East Asia.

The shape of the distribution of exposure across all CMIP3 models varies by region and type of exposure. This means that climate change impacts studies should try to use climate change projections from an ensemble of climate models that best represent the range across all GCMs available. It is not always computationally feasible to use *all* members of an ensemble (e.g. the CMIP3 models), however, and in such cases a careful and thoughtful selection of GCMs should be made, e.g. by considering where each GCM sits on the range of all GCMs in the ensemble. Otherwise there is a risk of selecting only GCMs that represent either the tail, or part of a bimodal distribution, for instance, and thus underestimating or overestimating the range of possible outcomes. While GCM performance metrics present a method for the selection of GCMs in impact studies (Wilby 2010), there remains a strong argument that all available GCMs should be used regardless because there is no difference in the projections from “better” GCMs when compared with “weaker” GCMs, at least where precipitation projections are of relevance (Chiew et al. 2009). Moreover, no single GCM may consistently out-perform all others when variables beyond precipitation only are considered (Gleckler et al. 2008).

We found that some climate change patterns result in more people exposed to an *increase* in water scarcity than people exposed to a *decrease*, at the global-scale (note that a “net water scarcity change” cannot be calculated by summing the increase and decrease in exposure for the reasons outlined by Arnell et al. (2011)). This contrasts with previous studies that used many less climate change patterns than we applied here and found consistently that a greater proportion of the global population is exposed to a decrease in water scarcity than

an increase (Arnell 2004; Hayashi et al. 2010). The sensitivity of relative increases and decreases in exposure to climate change pattern adds weight to the argument that all available GCMs should be used in water resource climate change impact assessments, where possible.

Similar to earlier work (Gosling et al. 2010; Arnell 2004), we found that projections of water scarcity are substantially more sensitive to climate change pattern than emissions scenario. However, this assessment has highlighted an appreciable sensitivity to the water scarcity indicator threshold that is used. Moreover, this is an important caveat of our analysis, since all estimates of water scarcity presented here are based upon global-scale generalisations about what it means to be in a situation of water scarcity. In particular, the application of the WSI is traditionally based upon water withdrawals instead of actual consumption. To some extent, this could mean that water scarcity measured by the WSI is overestimated in watersheds where withdrawn water is predominantly used either several times (e.g. hydropower) or returned downstream for other users instead of being consumed (e.g. some parts of the US). However, this limitation is less relevant to locations where water withdrawals are used predominantly for irrigation, where the water is also consumed and not returned to the system.

Average annual runoff was used as input to the water resources model. Thus in our modelling approach, an increase in average annual runoff can benefit society through a decrease in water scarcity. On the other hand, however, this could be tempered by an increase in flood risk, which we did not consider in this study, but we have elsewhere (Arnell and Gosling 2013). Other caveats include assumptions involving the parameters used both in the pattern-scaling (Todd et al. 2011) and Mac-PDM.09 (Gosling and Arnell 2011), and the assumed rates of population change (for each SRES scenario only one population projection was used). Additionally, by using a single global hydrological model we considerably underestimated hydrological model uncertainty, which only recently has been shown to be appreciable (Hagemann et al. 2013) but we note that Haddeland et al. (2011) showed that under present-day climate forcing, Mac-PDM.09 was located towards the middle of the range in simulated runoff across 5 global hydrological models. The net effect of these caveats is that the estimates of exposure to water scarcity should not to be taken too literally as actual impacts or “hardship” but rather as an indication of the relative effects of different emissions, climate and population scenarios.

We conducted this assessment at a time when a new set of global change scenarios was being released; the GCMs of CMIP5 (Taylor et al. 2011) with the Representative Concentration Pathways (RCPs; van Vuuren et al. (2011)) and the Shared Socio-economic Pathways (SSPs; Kriegler et al. (2012)). A comparison of our CMIP3 SRES A2 simulations to CMIP5 RCP8.5 SSP3 (see Online Resource 14 for methods and results) suggests that our conclusions are robust across the CMIP3 and CMIP5 models because the estimates of water scarcity are broadly consistent.

Acknowledgments Please see Online Resource 15.

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

References

- Alcamo J, Florke M, Marker M (2007) Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrol Sci J* 52:247–275
- Arnell NW (1999) Climate change and global water resources. *Glob Environ Chang* 9(Supplement 1):S31–S49

- Arnell NW (2004) Climate change and global water resources: SRES emissions and socio-economic scenarios. *Glob Environ Chang* 14:31–52
- Arnell NW, Gosling SN (2013) The impacts of climate change on river flow regimes at the global scale. *J Hydrol* 486:351–364
- Arnell NW, van Vuuren DP, Isaac M (2011) The implications of climate policy for the impacts of climate change on global water resources. *Glob Environ Chang* 21:592–603
- Arnell NW, Lowe JA, Brown S, Gosling SN, Gottschalk P, Hinkel J, Lloyd-Hughes B, Nicholls RJ, Osborn TJ, Osborne TM, Rose GA, Smith P, Warren RF (2013) A global assessment of the effects of climate policy on the impacts of climate change. *Nat Clim Chang* 3:512–519
- Chiew FHS, Teng J, Vaze J, Kirono DGC (2009) Influence of global climate model selection on runoff impact assessment. *J Hydrol* 379:172–180
- Gleckler PJ, Taylor KE, Doutriaux C (2008) Performance metrics for climate models. *J Geophys Res Atmos* 113(D6)
- Gosling SN, Arnell NW (2011) Simulating current global river runoff with a global hydrological model: model revisions, validation, and sensitivity analysis. *Hydrol Processes* 25:1129–1145
- Gosling SN, Bretherton D, Haines K, Arnell NW (2010) Global hydrology modelling and uncertainty: running multiple ensembles with a campus grid. *Philos Trans R Soc A Math Phys Eng Sci* 368:4005–4021
- Gosling SN, McGregor GR, Lowe JA (2012) The benefits of quantifying climate model uncertainty in climate change impacts assessment: an example with heat-related mortality change estimates. *Clim Chang* 112:217–231
- Haddeland I, Clark DB, Franssen W, Ludwig F, Voß F, Arnell NW, Bertrand N, Best M, Folwell S, Gerten D, Gomes S, Gosling SN, Hagemann S, Hanasaki N, Harding R, Heinke J, Kabat P, Koiraal S, Oki T, Polcher J, Stacke T, Viterbo P, Weedon GP, Yeh P (2011) Multimodel estimate of the global terrestrial water balance: setup and first results. *J Hydrometeorol* 12:869–884
- Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, Hanasaki N, Heinke J, Ludwig F, Voß F (2013) Climate change impact on available water resources obtained using multiple global climate and hydrology models. *Earth Syst Dyn* 4:129–144
- Harris I, Jones PD, Osborn TJ, Lister DH (2012) Updated high-resolution grids of monthly climatic observations: the CRU TS3.10 data set. *Int J Climatol* In press
- Hayashi A, Akimoto K, Sano F, Mori S, Tomoda T (2010) Evaluation of global warming impacts for different levels of stabilization as a step toward determination of the long-term stabilization target. *Clim Chang* 98(1–2)
- Kriegler E, O’Neill BC, Hallegatte S, Kram T, Lempert RJ, Moss RH, Wilbanks T (2012) The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. *Glob Environ Chang* 22:807–822
- Kummu M, Ward PJ, Moel H, Varis O (2010) Is physical water scarcity a new phenomenon? global assessment of water shortage over the last two millennia. *Environ Res Lett* 5:034006
- Meehl GA, Covey C, Taylor KE, Delworth T, Stouffer RJ, Latif M, McAvaney B, Mitchell JFB (2007a) THE WCRP CMIP3 multimodel dataset: a new era in climate change research. *Bull Am Meteorol Soc* 88:1383–1394
- Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao Z-C (2007b) Global climate projections. In: Solomon S, Qin D, Manning M et al (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 747–845
- Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. *Nature* 438:347–350
- Oki T, Kanae S (2006) Global hydrological cycles and world water resources. *Science* 313:1068–1072
- Oki T, Agata Y, Kanae S, Saruhashi T, Yang D, Musiaki K (2001) Global assessment of current water resources using total runoff integrating pathways. *Hydrol Sci J* 46:983–995
- Revens C, Brunner J, Henninger N, Kassem K, Payne N (2000) *Pilot analysis of global ecosystems freshwater ecosystems*. World Resources Institute and Worldwatch Institute, Washington
- Rockström J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D (2009) Future water availability for global food production: the potential of green water for increasing resilience to global change. *Water Resour Res* 45:W00A12
- Shen Y, Oki T, Utsumi N, Kanae S, Hanasaki N (2008) Projection of future world water resources under SRES scenarios: water withdrawal. *Hydrol Sci J* 53:11–33
- Taylor KE, Stouffer RJ, Meehl GA (2011) An overview of CMIP5 and the experiment design. *Bull Am Meteorol Soc* 93:485–498

- Thompson JR, Green AJ, Kingston DG, Gosling SN (2013) Assessment of uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models. *J Hydrol* 486:1–30
- Todd MC, Taylor RG, Osborn TJ, Kingston DG, Arnell NW, Gosling SN (2011) Uncertainty in climate change impacts on basin-scale freshwater resources—preface to the special issue: the QUEST-GSI methodology and synthesis of results. *Hydrol Earth Syst Sci* 15:1035–1046
- Van Vuuren DP, Den Elzen MGJ, Lucas PL, Eickhout B, Strengers BJ, Van Ruijven B, Wonink S, Van Houdt R (2007) Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Clim Chang* 81:119–159
- Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. *Science* 289(5477):284–288
- Vuuren D, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt G, Kram T, Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith S, Rose S (2011) The representative concentration pathways: an overview. *Clim Chang* 109:5–31
- Wilby RL (2010) Evaluating climate model outputs for hydrological applications. *Hydrol Sci J* 55:1090–1093