Climate Change and Global Water Resources

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Climate change and global water resources

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Abstract

By 2025, it is estimated that around 5 billion people, out of a total population of around 8 billion, will be living in countries experiencing water stress (using more than 20% of their available resources). Climate change has the potential to impose additional pressures in some regions. This paper describes an assessment of the implications of climate change for global hydrological regimes and water resources. It uses climate change scenarios developed from Hadley Centre climate simulations (HadCM2 and HadCM3), and simulates global river flows at a spatial resolution of $0.5 \times 0.5^{\circ}$ using a macro-scale hydrological model. Changes in national water resources are calculated, including both internally generated runoff and upstream imports, and compared with national water use estimates developed for the United Nations Comprehensive Assessment of the Freshwater Resources of the World. Although there is variation between scenarios, the results suggest that average annual runoff will increase in high latitudes, in equatorial Africa and Asia, and southeast Asia, and will decrease in mid-latitudes and most subtropical regions. The HadCM3 scenario produces changes in runoff which are often similar to those from the HadCM2 scenarios — but there are important regional differences. The rise in temperature associated with climate change leads to a general reduction in the proportion of precipitation falling as snow, and a consequent reduction in many areas in the duration of snow cover. This has implications for the timing of streamflow in such regions, with a shift from spring snow melt to winter runoff. Under the HadCM2 ensemble mean scenario, the number of people living in countries with water stress would increase by 53 million by 2025 (relative to those who would be affected in the absence of climate change). Under the HadCM3 scenario, the number of people living in countries with water stress would rise by 113 million. However, by 2050 there would be a net reduction in populations in stressed countries under HadCM2 (of around 69 million), but an increase of 56 million under HadCM3. The study also showed that different indications of the impact of climate change on water resource stresses could be obtained using different projections of future water use. The paper emphasises the large range between estimates of "impact", and also discusses the problems associated with the scale of analysis and the definition of indices of water resource impact.

Keywords: Climate change; Global water resources; Global runoff; Hydrological impacts of climate change

1. Introduction

Global warming, due to the enhanced greenhouse effect, is likely to have significant effects on the hydrological cycle (IPCC, 1996). The hydrological cycle will be intensified, with more evaporation and more precipitation, but the extra precipitation will be unequally distributed around the globe. Some parts of the world may see significant reductions in precipitation, or major alterations in the timing of wet and dry seasons. The Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) warned that global warming would lead to increases in both floods and droughts.

Many aspects of the environment, economy and society are dependent upon water resources, and changes in the hydrological resource base have the potential to severely impact upon environmental quality, economic development and social well-being. There have, so far, been few assessments (e.g. Alcamo et al., 1997) at the global scale of the potential impacts of climate change on water resources.

Climate change, however, is just one of the pressures facing water resources and their management over the next few years and decades (see Gleick, 1998). In the most general terms, there are both supply-side and demand-side pressures. The supply-side pressures include climate change (reducing or increasing the amount of water available), but also include environmental degradation, where for example pollution reduces the amount of water available for use. Demand-side pressures include population growth and concentration, leading to increased demands for domestic, industrial and agricultural

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(particularly irrigation) water, increased environmental demands, and the effects of changes in the way demands for water are managed. Climate change may affect the demand side of the balance as well as the supply side.

In 1997, the United Nations published a Comprehensive Review of the Freshwater Resources of the World (WMO, 1997). The assessment included four components: collation of up-to-date national-level data on water resources and their use, the development of projections of future use (to 2025 and 2050), description of present and future pressures, and the assessment of strategies and options for the sustainable development of world water resources. The assessment highlighted the effects of increasing population and economic development on water resource availability. It estimated that approximately one-third of the world's population currently lives in countries experiencing moderate to high water stress, and forecast that by 2025 as much as two-thirds of a much larger world population could be under stress conditions simply due to the rise in population and water use.

This paper describes an assessment of the effects of climate change on water resources stresses, over and above the effects of population and economic change. The study represents one component of a "Fast Track" assessment of the impacts of climate change across several sectors at the global scale (Parry et al., 1999), based on climate change experiments conducted by the Hadley Centre. The paper first outlines the methodology used, then discusses the indices of water resources stress employed. The rest of the paper first describes changes in hydrological characteristics at the global scale, and then considers effects on water resource stresses.

2. Methods and data sources

2.1. Introduction

The project methodology essentially follows the standard climate change impact assessment approach (Parry and Carter, 1998). The study uses scenarios based on the HadCM2 and HadCM3 climate change experiments (Hulme et al., 1999), and applies these to a global baseline climatology (New et al., 1999a,b). A macro-scale hydrological model (Arnell, 1999a) is then used to simulate river flows across the globe at a spatial resolution of $0.5 \times 0.5^{\circ}$ (between 1800 and 2700 km^2). Changes in national water resource availability are then calculated, and used with projections of future national water resource use to estimate the effects of climate change on water resources stresses at the global scale.

2.2. The hydrological model and its application

The hydrological model used is a conceptual water balance model, which calculates the evolution of the components of the water balance at a daily time-step, treating each $0.5 \times 0.5^{\circ}$ cell as a separate catchment (Arnell, 1999a). Precipitation falls as snow if temperature is below a certain threshold, and snow melts once temperature rises above another threshold. Potential evaporation is calculated using the Penman–Monteith formula. Actual evaporation is a function of potential evaporation and soil moisture content: soil moisture is replenished when precipitation exceeds actual evaporation and drainage from the soil, and is depleted by evaporation and drainage. The soil moisture storage capacity varies statistically across the cell/catchment. "Quick response" runoff at any time occurs from the parts of the cell/catchment that have saturated soils at that time. "Slow response" runoff is a function of the amount held in deep soil and groundwater storages, which are filled by drainage from the upper soil layer. The rate of potential evaporation varies with catchment vegetation, and vegetation also intercepts precipitation: the intercepted precipitation is assumed to evaporate. Model parameters defining soil and vegetation properties are taken from spatial data bases. The model used in this study is a slightly enhanced version of that described in Arnell (1999a), with the following modifications:

1. The model can recognise different types of vegetation. In the current application, 13 land cover classes are distinguished, taken from the global land cover data set produced by de Fries et al. (1998). The original data are presented at 8 km resolution: the dominant land cover class for each $0.5 \times 0.5^{\circ}$ cell was determined with the ARC/INFO GIS package. Each land cover class is allocated a fractional cover, leaf area index, stomatal resistance (used in calculating the potential evaporation), canopy storage capacity (used to define interception) and root depth (used to define soil moisture storage).
2. The absolute soil moisture storage capacity in each grid cell is a function of the soil texture (as in the earlier version of the model) and the rooting depth of the vegetation (this was previously assumed constant globally).

The model is run to simulate 30 years of streamflow (at a daily time step, although monthly totals only are saved and output), using the Climatic Research Unit gridded $0.5 \times 0.5^{\circ}$ 1961–1990 climate time series (New et al., 1999a,b). Streamflow is not routed from cell to cell.

The volume of runoff generated within a country is calculated by summing the area-weighted runoff produced in each of the grid cells within the country. Imports of water into a country from upstream are determined by summing the area-weighted runoff produced in the grid cells draining into the country. These cells were identified by superimposing the $0.5 \times 0.5^{\circ}$ global watershed data set produced by RIVM (Klepper, 1996, and updated at the

University of Kassel) onto national boundaries within the ARC/INFO GIS package, and manually coding watershed segments upstream of each country. Total national runoff is equal to the sum of the water generated in the country and imported from upstream.

2.3. Water use data and projections of future use

2.3.1. Present water use data

Data on national water resources and withdrawals were taken from the database collated for the Comprehensive Assessment (Shiklomanov, 1997). The data include estimates of the average annual runoff generated within the country (internal resources), the average annual runoff imported from upstream, and total withdrawals (in 1995) of freshwater within the country. The present study uses 1990 as a baseline year, so withdrawals for 1990 were estimated from the 1995 figures assuming the same *per capita* use.

At the global scale, the largest user of water is irrigated agriculture. It represents 70% of present freshwater withdrawals (Raskin et al., 1997), with these withdrawals concentrated in particular countries. Industrial uses account for 22% globally, through manufacturing and, particularly, thermoelectric power generation (for cooling). Much of the cooling water is in fact returned to the water system, although at higher temperature. Domestic, municipal and service industry use accounts for just 8% of global water use. The proportions of water used in each sector by country, however, can vary considerably around these global estimates. In much of Europe, for example, water used for domestic, municipal and service industries is a very high proportion of total demand.

2.3.2. Future water use

There are several factors influencing the growth of future water resource use:

- Population growth: an increase in population means greater demand for water.
- Population concentration: population, particularly in developing countries, is becoming increasingly concentrated in large cities. This has two implications. First, water use is different in an urban environment than in a rural environment. For example, water will be supplied through a pipe network, so more is used than in rural areas, and water is lost through leakage. Second, the increasing concentration of demand means greater pressure on resources in specific areas.
- Industrial change: industrial development increases the demand for water, but industrial restructuring may reduce it (as in large parts of Europe). As water is seen as more of an economic good, it will be used more efficiently in industry.
- Expansion of irrigation: the growth in irrigated areas will lead to more usage by agriculture, but this may be offset to a certain extent by improvements in irrigation efficiency.
- Water use efficiency and demand management: more generally, increased water use efficiency and demand management measures will bring down domestic, municipal and service industry demands, particularly in western countries.
- Environmental requirements: increasing demands for environmental protection will put additional constrains on water resource use. These demands are currently *not* included in estimates of resource use.

Table 1
The conventional development scenario (Raskin et al., 1997)

Sector	Assumptions
Domestic, municipal and service sector	i. Assume change in water use per person ii. Assume non-OECD country usage converges to OECD usage
Industry	i. Reduce intensity (per $1000 GDP) of manufacturing use in OECD countries ii. Intensity of use (per $1000 GDP) in non-OECD countries converges to OECD usage iii. Usage for petroleum refining and cooling change in proportion to energy usage
Agriculture	i. Assume increase in irrigated area ii. Assume increase in cropping intensity iii. Assume increase in irrigation water intensity (to increase yield) iv. Assume increase in irrigation use efficiency

Estimates of future water resource use are notoriously difficult to make. Simple approaches include extrapolation of past trends or assuming constant per capita demands, but these have been shown to be very inaccurate in the past. As part of the Comprehensive Assessment, scenarios for future water use were developed from assumptions about possible changes in the components of demand (Raskin et al., 1997). The conventional development scenario (CDS) projected water use to 2025 and 2050 by sector and by regional economic grouping. Table 1 summarises in qualitative terms the assumptions made for each sector.

The largest percentage increases are in the developing world, particularly in Africa.The largest absolute increases are in southeast Asia. Agriculture remains the biggest user, although its share of the total falls.

"Mid-range", high and low-case projections were produced, assuming different rates of economic growth and technological improvements but the same rate of population growth. Fig. 1 shows change in global water use by 2025 and 2050, under the three projections. By 2025, global water use will have increased under the mid-range

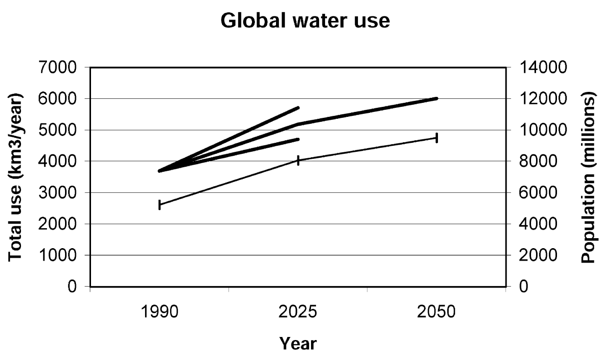

Fig. 1. Global water resource withdrawals, 1990–2050. The thick lines show total withdrawals, under the mid-range, low and high (to 2025 only) Conventional Development Scenarios. The thin line shows the total population.

scenario by 35% over 1995 (with a range from 23 to 50% under the low and high projections), and by 67% by 2050.

The CDS scenarios were derived using a different (and slightly higher) set of population projections to the World Bank 1995 projections used in the DETR Fast Track project (Hulme et al., 1999). The CDS estimates of national water use for 2025 and 2050 were therefore rescaled by the ratio of the different population estimates.

Estimates of national water withdrawals by 2085 were made by extrapolating the change in *per capita* usage between 2025 and 2050 under the CDS scenarios, and applying to the projected national population totals for 2085.

The water use scenarios used in this study assume no effect of climate change on the demand for water. In practice, climate change is likely to increase demand for water, particularly for irrigation purposes.

2.4. Climate change scenarios

Climate change scenarios were taken from two sets of experiments with Hadley Centre models (Hulme et al., 1999). One set used the HadCM2 model, and comprised four "ensemble" simulations (the same model, run four times from slightly different initial conditions). An ensemble mean scenario was also generated. Each simulation is forced by a 1% per year compound increase in equivalent CO_2 concentrations from 1990 to 2100. These scenarios are denoted by GGa1 to GGa4 for the four members, and GGax for the ensemble mean. The sixth scenario was taken from the HadCM3 simulation, representing one model simulation also with a 1% per year compound increase in equivalent CO_2 concentrations.

From each model simulation, 30-year monthly means of temperature, precipitation, windspeed, vapour pressure and "cloud cover" (indexed by top of cloud reflected short-wave radiation) were extracted by the Climatic Research Unit for the periods 1961–1990 (representing the baseline), 2010–2039 (the "2020s"), 2040–2069 (the "2050s") and 2070–2099 (the "2080s"). More details are given in Hulme et al. (1999). None of the scenarios assume changes in sulphate aerosol emissions.

The GCM scenarios are applied to the $0.5 \times 0.5°$ climatology *without* spatial downscaling or temporal smoothing. Absolute changes in temperature, precipitation and vapour pressure were applied to the baseline climatology, and percentage changes were applied to windspeed and "cloud cover". Net radiation was calculated from cloud cover, temperature and humidity using procedures described by Shuttleworth (1993).

The direct effect of CO_2 enrichment on potential evaporation is assumed to be negligible at the catchment scale when simulating future runoff. Land use within each catchment is also assumed constant.

3. Indices of water resource pressure

A number of indices of water resource pressures have been proposed and used in global and continental scale assessments (Falkenmark and Lindh, 1976; Raskin et al., 1997). Raskin et al. (1997) identified three broad aspects of a nation's vulnerability to water resources stress: resource availability, resource reliability and the capacity to cope. Most emphasis has been placed so far in the literature on indices of total resource availability, particularly in relation to resource use. Also, all of these assessments (such as the Comprehensive Assessment) have used national-level indices. These can hide enormous within-country variation, but global-scale analyses have so far been limited by the availability of data. There are, however, other dimensions of water resources stress, related not so much to the volume of water available but rather to *access* to that water: it is possible for a country or basin with apparently abundant water resources actually to be under extreme water stress, simply because that water is not widely accessible. It may be unavailable to rural populations because of the lack of a distribution network (who therefore have to rely on limited local, perhaps low-quality, sources), for example, or could already be allocated to other users. Several countries in semi-arid regions are apparently well-resourced, but much of the available water is concentrated in major rivers whose flows are often generated in more humid headwaters: large proportions of the rural population are distant from these major river courses, and are reliant on locally generated water. Whilst there are data (of variable quality) on national proportions of populations with "access to safe water" (e.g. Gleick, 1998), it is difficult to translate these into indicators of stress.

The simplest index of resource availability is average annual renewable resource (runoff generated within a country, runoff from upstream and groundwater recharge that reappears as runoff) per capita (Falkenmark

Table 2
Use/resource ratio classes used in the comprehensive assessment

Use/resource	< 10%	10–20%	20–40%	> 40%
Class	No stress	Low stress	Medium stress	High stress

and Lindh, 1976). A value of less than 2000 m^3 per capita is widely believed to indicate a stressed condition. This index, however, does not account for differences in the intensity of use (and particularly for the considerable variation in use for irrigation). A more realistic index is therefore the ratio of withdrawals to average annual resources. With withdrawals greater than 20% of the renewable resources, water stress is acknowledged to be a limiting factor on development (Falkenmark and Lindh, 1976). The Comprehensive Assessment calculated the use/resource ratio, dividing countries into four classes, as shown in Table 2.

The major weakness of this index is that it is based on average annual runoff: in practice, not all this runoff may be potentially available for use, and the proportion that is will very significantly between countries. The more stable the runoff regime, the greater the proportion of annual runoff that is potentially available as a resource (in semi-arid areas, for example, only a small proportion may be accessible because flows are concentrated in a short time), and the greater the amount of storage in lakes and reservoirs, the greater the proportion of runoff that is available. A refinement to the index could use seasonal runoff totals or the annual resource with a defined return period.

The present study uses the simple use/resource ratio, calculated at the national scale, for consistency with other global water resources assessments, specifically the Comprehensive Assessment. The limitations of such an index and scale of analysis are acknowledged.

4. Effect of climate change on hydrological regimes at the global scale

4.1. Change in the water balance

The climate change scenarios used in this assessment have a geographically variable change in precipitation — high latitude, equatorial and some sub-tropical regions have an increase, mid-latitude and some sub-tropical regions have a decrease (Hulme et al., 1999) — and a general increase in temperature. Potential evaporation, as calculated by the Penman–Monteith formula, increases too, by on average 7.5–10% by the 2020s (depending on scenario), 13–18% by the 2050s, and 19–27% by the 2080s.

Fig. 2 shows the change in average annual runoff, by the 2050s, under the HadCM2 ensemble mean scenario (GGax) and HadCM3, together with the simulated baseline average annual runoff. The variations in change reflect not only the patterns of change in precipitation (Hulme et al., 1999), but also the general increase in potential evaporation: larger parts of the world show a reduction in annual runoff than see a reduction in annual precipitation.

The broad runoff patterns as simulated by the four HadCM2 ensemble members (GGa1 to GGa4) are similar to themselves and to the ensemble mean (GGax). Runoff increases in high latitudes, equatorial regions and some sub-tropical areas, but decreases elsewhere. There are some regional differences between the ensemble members. For example, member GGa1 simulates a much smaller decrease in runoff across southern Europe than the other three members, but its simulated increase in runoff in the southeast of the United States is smaller. Member GGa3 simulates a much larger decrease in runoff in southern Siberia than the others. The patterns from the ensemble members are also less stable from one time period to another than the pattern from the ensemble mean.

The change in runoff from HadCM3 GGa1, however, has a rather different pattern to those from the HadCM2 scenarios. Runoff reduces considerably across the Amazon basin and across much of the United States. In contrast, runoff increases under HadCM3 across southern Asia, and particularly across the Indian subcontinent. The difference in runoff patterns largely reflects the difference in precipitation change patterns, but increases in potential evaporation also tend to be generally higher under HadCM3. Potential evaporation is higher under HadCM3 for several reasons: the temperature increase is greater in many regions, the vapour pressure increase is generally smaller (leading to a greater increase in vapour pressure deficits), windspeeds are slightly higher, and the patterns of net radiation change are different, reflecting the different spatial patterns of precipitation change.

Table 3 shows the percentage change in annual runoff, rainfall and potential evaporation across the world land area, by the 2020s, 2050s and 2080s, under the six scenarios.

Global land precipitation increases under all scenarios, although the increase is lower under HadCM3. Potential evaporation too increases, this time with the largest increase under HadCM3. Global runoff decreases under HadCM3, but shows very little net change with the HadCM2 scenarios.

Fig. 3 shows the percentage change in annual precipitation, potential evaporation and runoff by the 2050s for approximately 40 major river basins (listed in Table 4 and mapped in Fig. 4).

Increases in potential evaporation are clearly higher in most basins under HadCM3 than HadCM2, although in parts of Asia they are lower. The pattern of runoff change

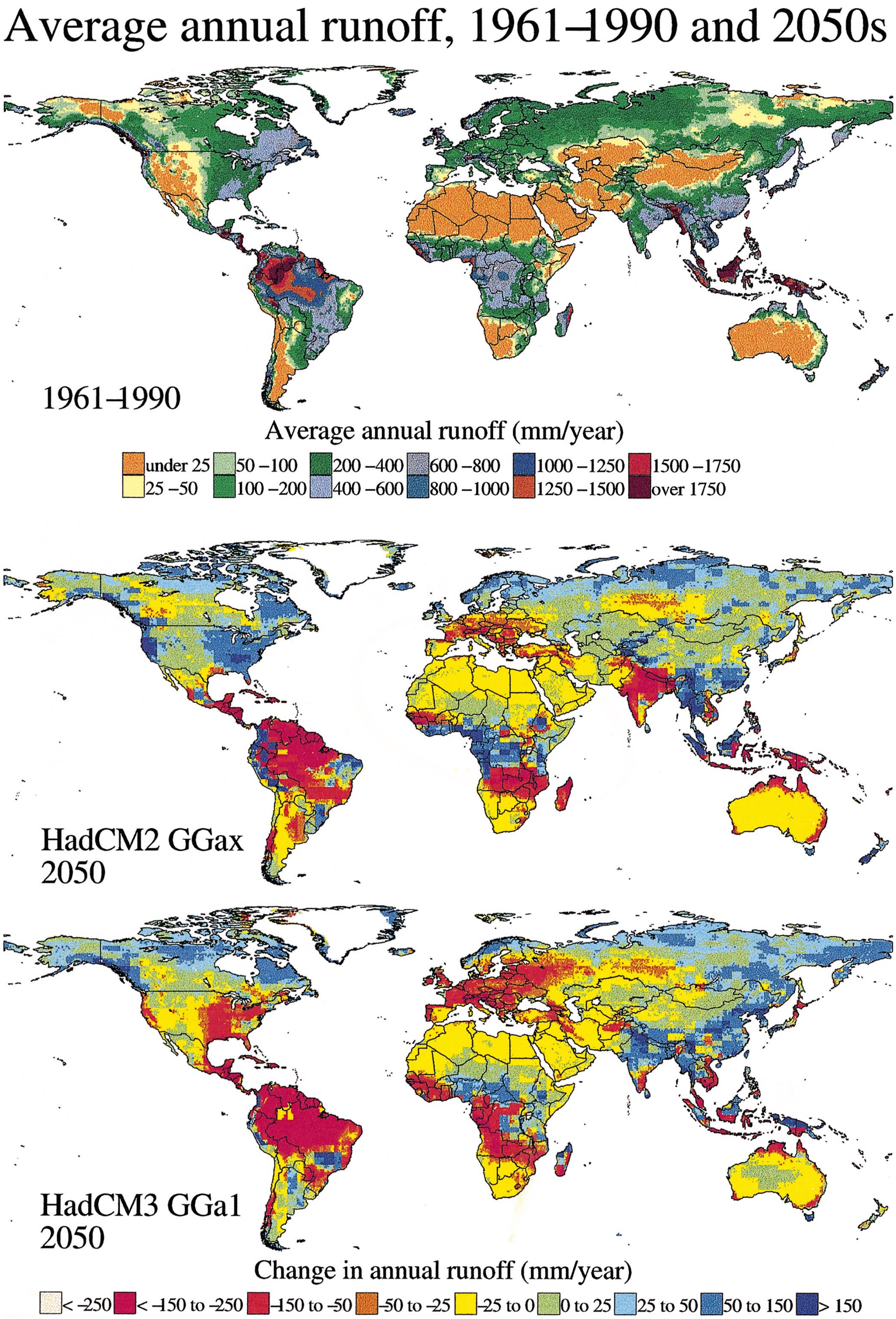

Fig. 2. Change in average annual runoff by the 2050s.

Table 3
Percentage change in global land annual water balance components, relative to 1961–1990

	HadCM2					HadCM3
	GGa1	GGa2	GGa3	GGa4	GGax	GGa1
Precipitation						
2020s	3.4	2.7	2.2	2.4	2.6	0.6
2050s	4.9	5.2	4.8	4.8	4.8	1.5
2080s	7.5	7.1	6.4	7.1	6.9	2.1
Potential evaporation						
2020s	7.7	8.0	8.2	8.7	7.5	10.0
2050s	13.6	12.6	12.8	13.8	13.4	18.4
2080s	20.3	19.8	19.3	19.6	20.0	27.3
Runoff						
2020s	2.3	− 0.7	− 1.2	− 0.5	0.8	− 7.4
2050s	− 0.1	0.7	− 0.3	1.1	− 0.5	− 10.5
2080s	0.9	0.6	− 0.7	1.0	− 0.4	− 14.7

follows closely the pattern of precipitation change, although the magnitudes of relative change are greater. Fig. 3 emphasises the range between the four HadCM2 ensemble members — and shows how HadCM3 is often outside the range spanned by the HadCM2 ensemble. The biggest percentage decreases in runoff are seen in southern Africa, Europe, and parts of South America, with the largest percentage increases in Asia, and north America (except under HadCM3).

4.2. Change in snowfall

A rise in temperature generally means that less precipitation falls as snow, although the absolute amount of snowfall may increase if precipitation increases during the winter season. Fig. 5 shows the simulated northern hemisphere end of March snow cover, under the baseline climate and by the 2020s, 2050s and 2080s under the HadCM2 GGax scenario (the other HadCM2 scenarios are rather similar to GGax because the pattern is largely driven by temperature: HadCM3 shows a rather more extensive reduction in snow cover because of the higher temperature increase).

Across large parts of north America, northern China and eastern Europe, snow cover by the end of winter has been considerably reduced by the 2050s. This has implications for the timing of streamflow through the year — as indicated in the next section. In northern Asia, however, extra winter precipitation leads to an increase in March snow cover.

4.3. Change in monthly runoff regimes

Fig. 6 shows average monthly runoff regimes for 12 example locations, under the baseline climate and by the 2050 s under HadCM2 GGax. Both the southern English and the Italian cells are influenced by maritime climates, and by the 2050s there is little change in the timing of flows through the year: in southern England, however, the seasonal range is increased. The Belarus example illustrates the effect of the rise in temperature on snow cover. Snowmelt begins in March, rather than April, and the spring snowmelt peak is considerably reduced. Further east, in western Russia, the rise in temperatures has less effect on the timing of snowmelt, so the timing of the flow regime is little altered.

Table 4
Major river basins included in Fig. 3

River	Region	Area (10^3 km^2)
Volga	Russia	1501
Rhine	Central Europe	303
Danube	Central Europe	1311
Tigris	Middle East	455
Euphrates	Middle East	491
Nile	Africa	3022
Niger	West Africa	1948
Volta	West Africa	565
Scebeli	North East Africa	320
Zaire	Central Africa	4213
Ogooue	West central Africa	340
Rufiji	East Africa	202
Zambezi	Southern Africa	1752
Rovuma	East Africa	238
Betisboka	Madagascar	47
Limpopo	East Africa	529
Oranje	Southern Africa	625
Murray-Darling	Australia	1047
Moctezuma	Mexico	120
Orinoco	North Latin America	1219
Amazon	Latin America	6888
Parana	Southern Latin America	255
Colorado (SA)	Southern Latin America	484
Helmand-Rud	Iran	484
Khatanga	Northern Siberia	293
Lena	Russia	2324
Yenisey	Russia	1867
Kolyma	Northern Siberia	660
Ob	Russia	3426
Amur	East Asia	1750
Huang He	China	1074
Indus	Pakistan	1586
Yangtze	China	1719
Brahmaputra	Tibet/Bangladesh	780
Xijiang	China	517
Mackenzie	Northern Canada	1699
Yukon	Alaska	960
Koksoak	North east Canada	166
Colorado (NA)	West USA	701
Saskatchewan	Central Canada	525
Red	Central Canada	411
Mississippi	USA	3225

Note: i. The basins are listed in the same order as shown in Fig. 3.
ii. The basin area is as represented on a $0.5 \times 0.5^\circ$ resolution.

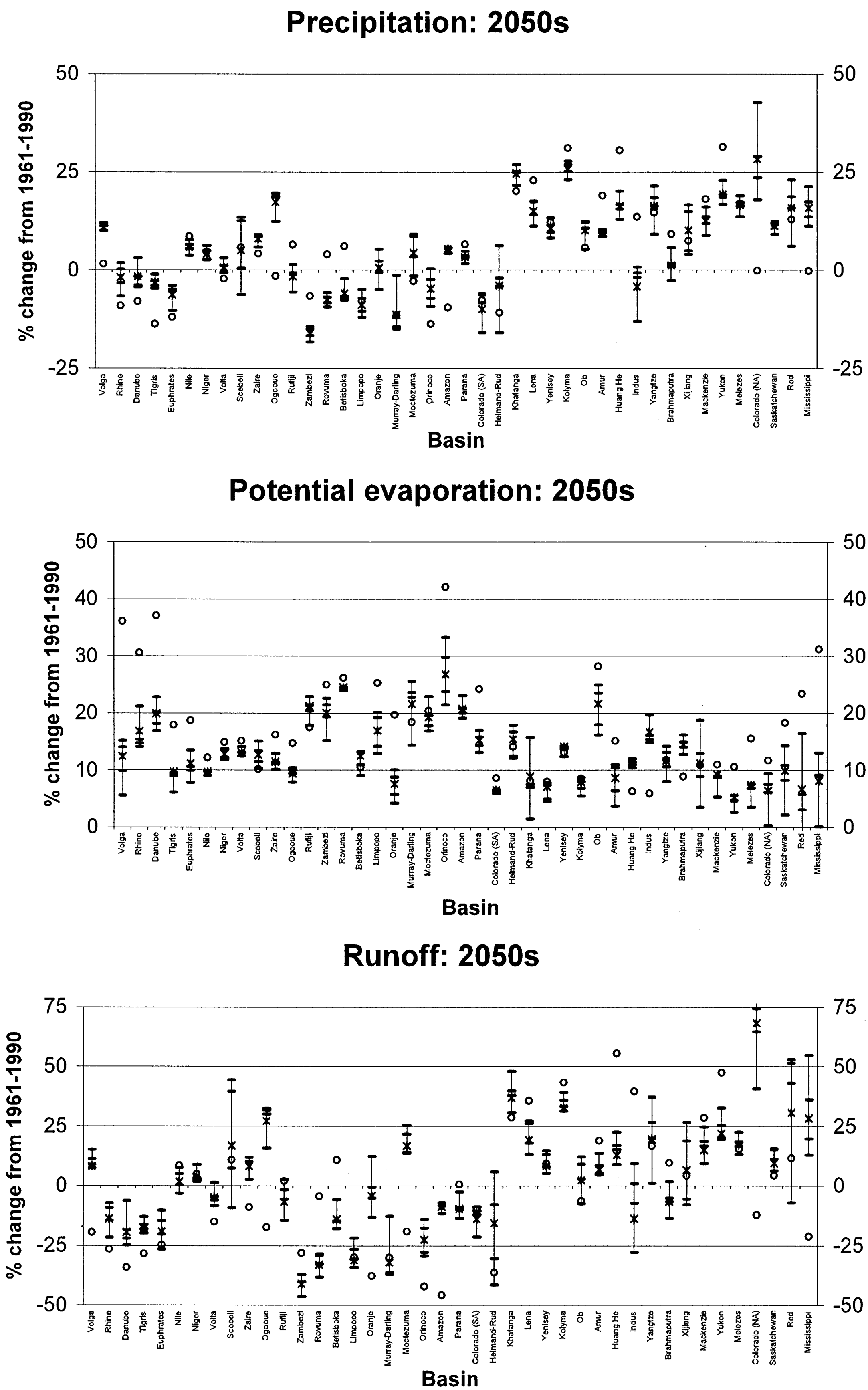

Fig. 3. Change in regional average annual rainfall, potential evaporation and runoff, by the 2050s, by major river basin.

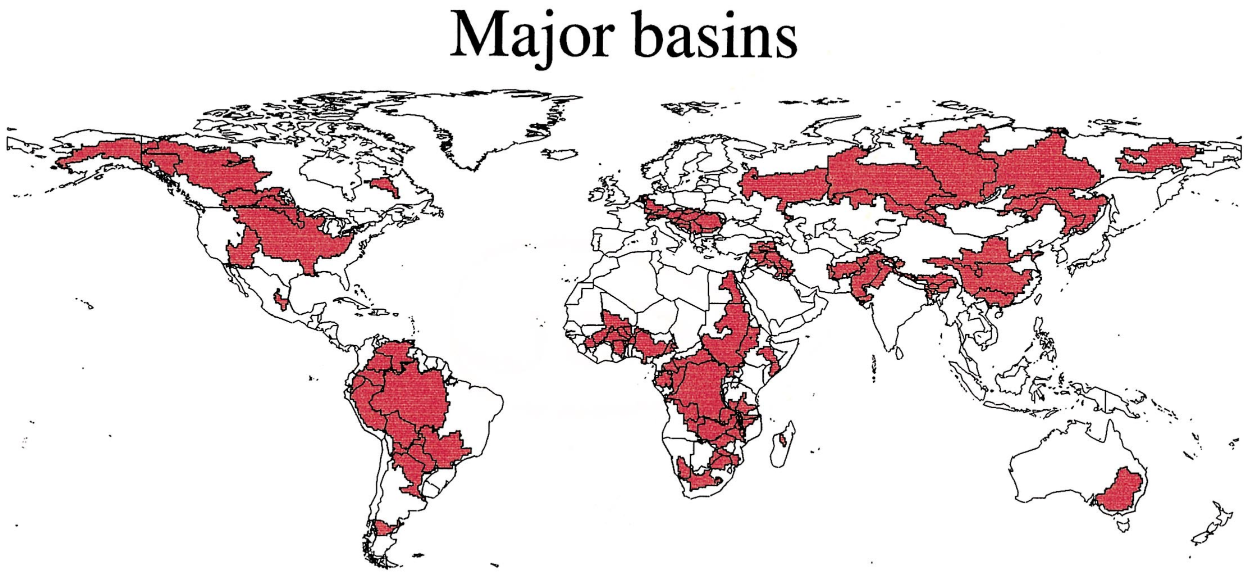

Fig. 4. Coverage of major river basins.

By the 2050s there are also few changes in the timing of flow in the Asian examples, although in Thailand the greatest increases are during the build up to the peak flow season (in June, July and August), and in eastern China the greatest effects are on flows during the drier part of the year: peak flows are little affected. There are also few changes in flow regime characteristics in the three African examples. In Ghana flows during the wet season are most affected, with dry season flows little altered (on average).

The two north America examples illustrate the effect of the reduction in the snowpack due to higher temperatures. In the Great Plains example, the first peak period (in March) is considerably reduced with flows occurring earlier, but the second peak (following rainfall in May and June) is little altered. In the northeast of the United States, flows during January and February are substantially increased by the 2050s, indicating a significant reduction in the extent and duration of snow cover.

4.4. Change in extremes

4.4.1. Change in high flows

Although the hydrological model used in this study simulates streamflow at the daily time scale, monthly total data only are archived. This is because the model parameters used to route daily streamflow have not been calibrated, and estimates of extreme daily flows may be very unreliable. The model includes "typical" routing parameters, tuned so that the simulated monthly flow regime approximates observed monthly flow regimes from medium-sized catchments (Arnell, 1999a). The index of high flows used in this study is the maximum monthly runoff total, with a return period of 10 years. Because of the generalised nature of the routing parameters, this index should be interpreted as representing the high flow properties in a "typical" catchment: the actual high flow properties in a grid cell may be rather different, due to the presence of, for example, wetlands, lakes or significant groundwater storage which dampens the variation in flow through time. Also, the index is based on monthly data: variations in short-duration flood flows from year to year may not be closely related to total monthly runoff. The 10-year return period maximum monthly runoff was estimated for each cell by fitting a Generalised Extreme Value distribution to the sample of 30 maximum monthly runoff totals. The selection of probability distribution is not critical, as the 10-year event is within the range of the data series.

Fig. 7 shows the change in the magnitude of the 10-year maximum monthly runoff, by the 2050s under the HadCM3 scenario. In general terms, the change in high flows reflects the pattern of change in annual runoff. However, the percentage change in the high flow indicator is generally considerably larger than the percentage change in annual runoff — because percentage change in seasonal runoff is also generally proportionately greater. Areas with particularly large percentage change in high flows include northwest north America and east Asia. As with annual runoff, there are differences in pattern between the HadCM2 and HadCM3 scenarios.

4.4.2. Change in low flows

In many parts of the world the lowest flows are zero, and may persist at this level for several months. An indicator of low flows defined in a temperate area (such as the deficit duration index used in Europe by Arnell, 1999b) may therefore not be appropriate everywhere.

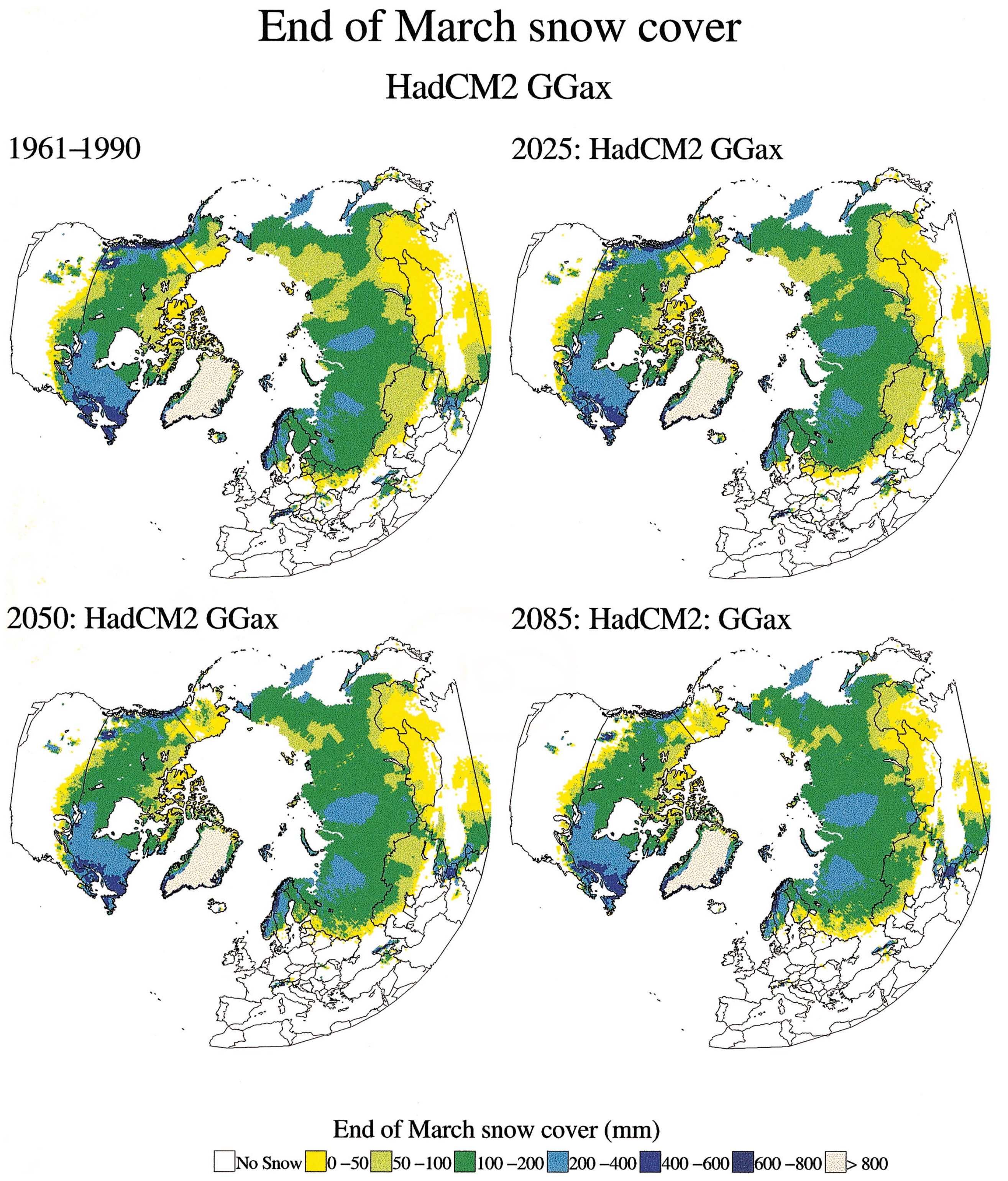

Fig. 5. End of March snow cover: HadCM2 GGax.

This study indexes low flows by the low annual total runoff (calendar year) with a return period of 10-years (the "one-in-10 year dry year"). It is estimated by interpolation from the ranked series of 30 annual runoff totals.

Fig. 7 shows the change in "low flows" by the 2050s, under the HadCM3 scenario. Again, the pattern of change is broadly similar to that for annual runoff, although the percentage changes are considerably greater.

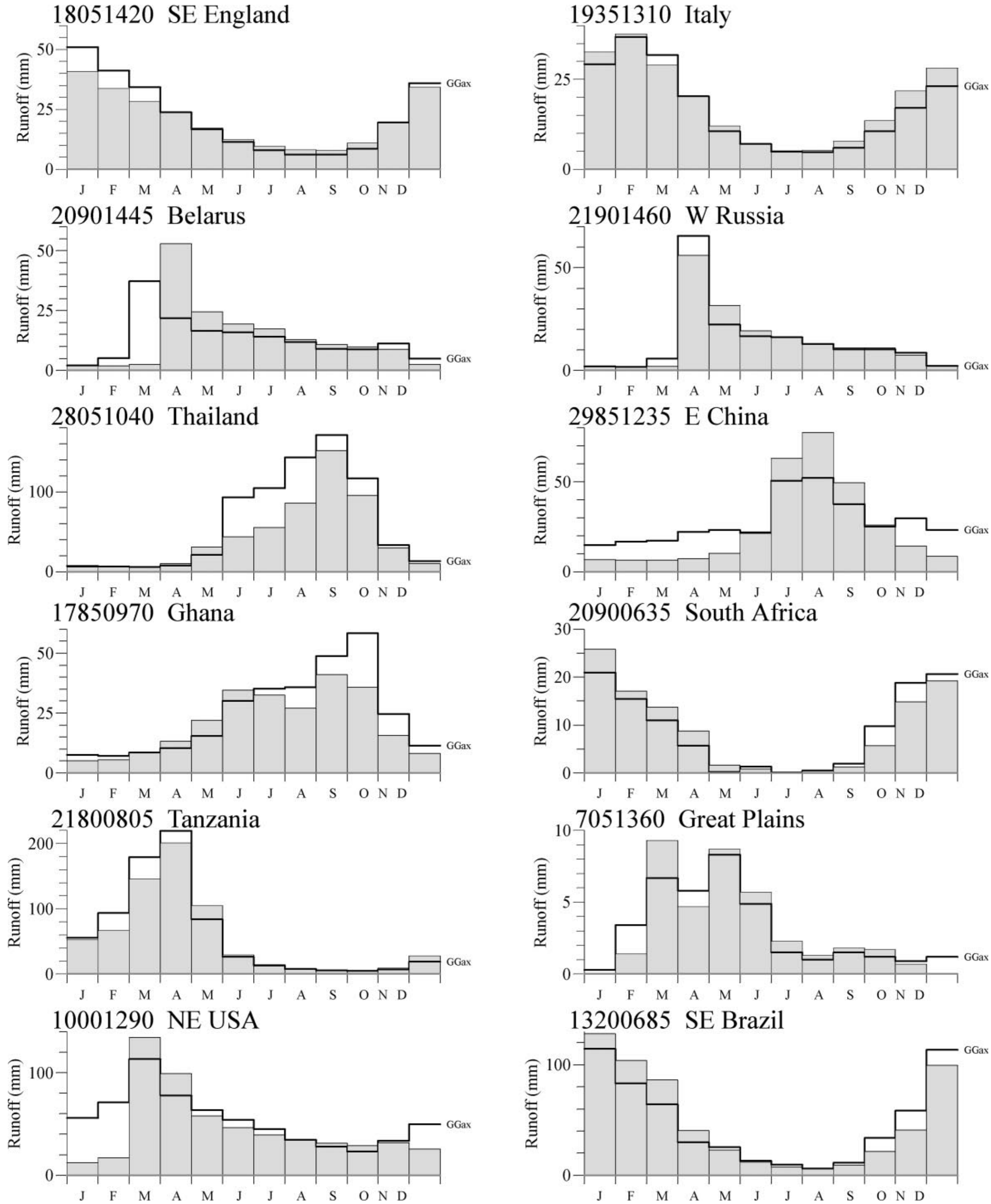

Fig. 6. Monthly runoff regimes for a sample of locations, under baseline and GGax (2050s) climates.

The bottom panel of Fig. 7 shows the parts of the world with an increase in the 10-year flood of greater than 10%, a reduction in the 10-year minimum annual runoff of more than 10%, and both an increase in "flood risk" and an increase in "drought risk" at the same time. Some small areas see both an increase in flooding and a decrease in drought.

5. Impacts on water resources

5.1. Present and future water resources stresses in the absence of climate change

In 1990, approximately one-third of the world's population (1750 million out of 5218 million) were living in

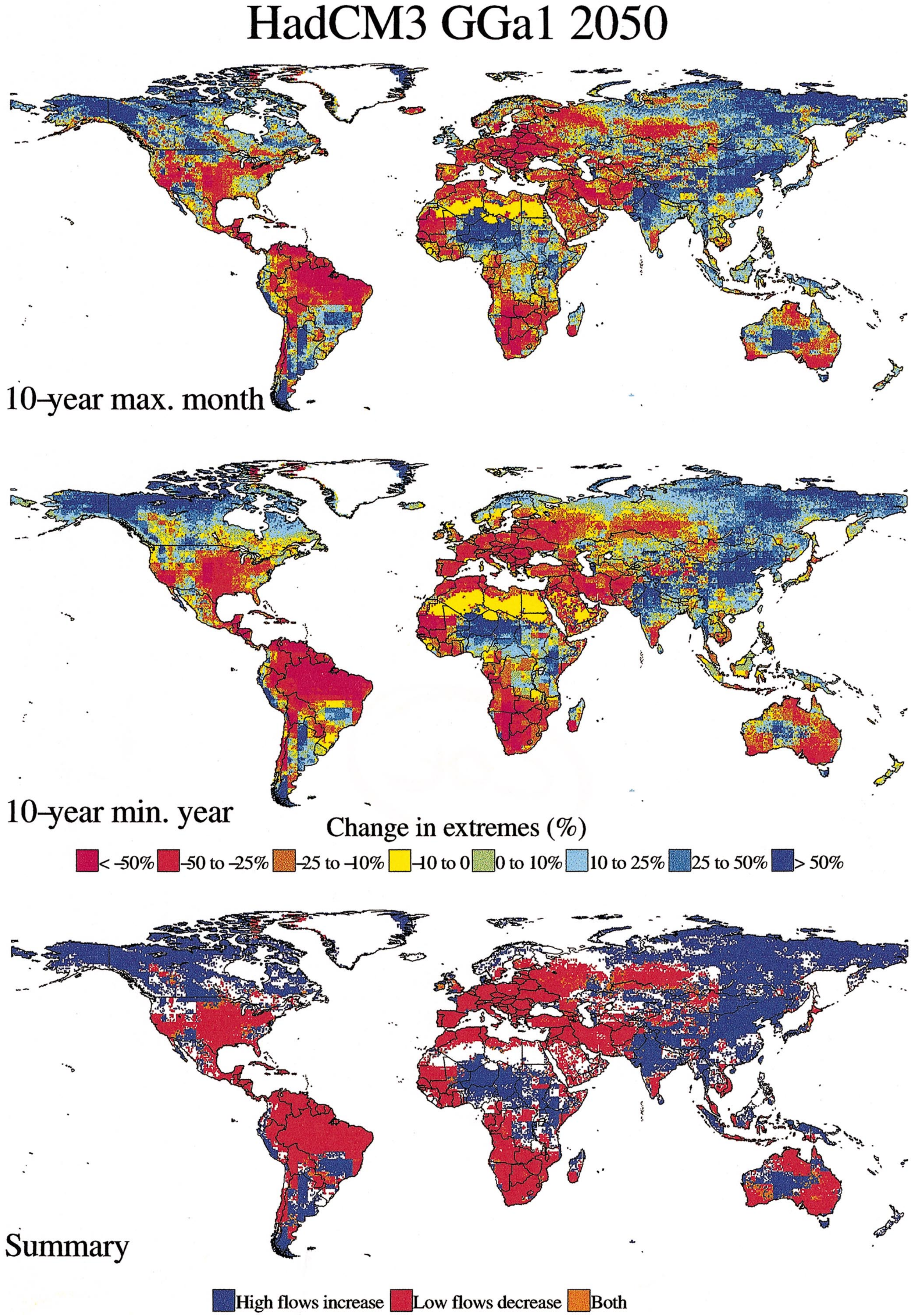

Fig. 7. Change in extremes by the 2050s, under HadCM3. The top panel shows change in the magnitude of the 10-year return period maximum monthly runoff, and the middle panel shows the change in the magnitude of the 10-year return period minimum annual runoff: the bottom panel shows the areas with an increase in flood, a decrease in low flows, or both.

Table 5
Present and future water resources stresses in the absence of climate change

Date	Total world population (millions)	Population (millions) living in countries using more than 20% of their water resource	Population (millions) living in countries using more than 40% of their water resource
1990	5218	1750	406
2025	8055	5028	2370
2050	9525	5974	3217
2085	10994	6464	5396

Note: World Bank 1994 medium population projections, and Comprehensive Development Scenario for water use (extrapolated to 2085).

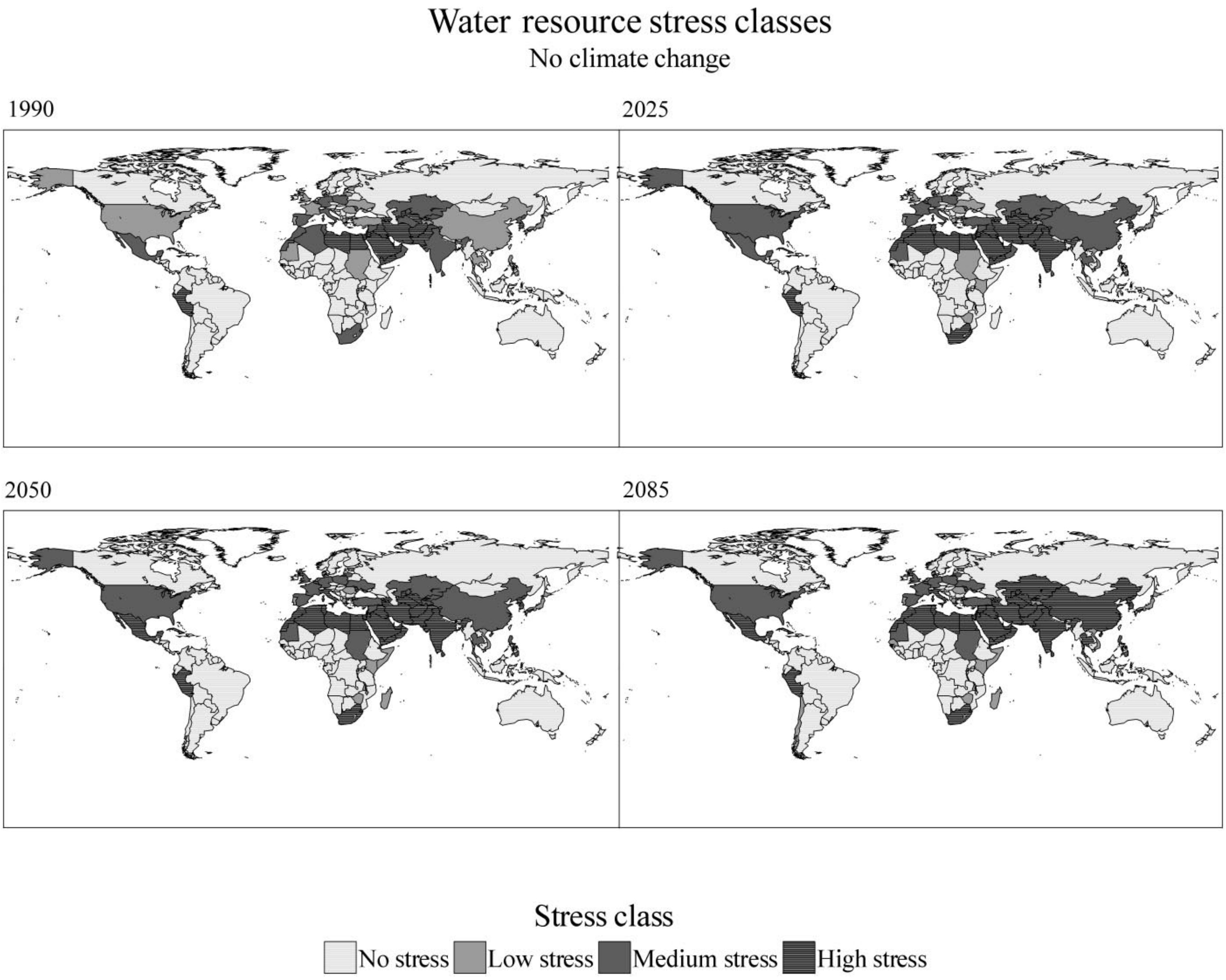

Fig. 8. Distribution of countries in four stress classes in 1990, 2025, 2050 and 2085, without climate change.

countries using more than 20% of their available resources. Table 5 presents the estimates for 2025, 2050 and 2085 under the Conventional Development Scenario, *in the absence of climate change* (note that the 2085 estimates are based on an extrapolation of the CDS).

Fig. 8 maps the distribution of countries, in 1990, 2025, 2050 and 2085, in the four water resources stress classes shown in Table 2. Stressed countries are concentrated in southern Asia, southern and northern Africa, around the Mediterranean, and in the Middle East.

Table 6
Change in number of people (millions) in countries using more than 20% of their resources, relative to the reference case (Table 5)

	HadCM2					HadCM3
	GGa1	GGa2	GGa3	GGa4	GGax	GGa1
2025	0	53	53	0	53	113
2050	− 36	− 46	− 352	− 17	− 69	56
2085	42	25	85	41	42	105

Table 7
Difference between the total population in countries where climate change increases stress, and where climate change decreases stress

	HadCM2					HadCM3
	GGa1	GGa2	GGa3	GGa4	GGax	GGa1
2025						
Increase	2554	2420	2529	2476	2705	1762
Decrease	2468	2654	2545	2545	2369	3373
Net	86	−235	− 16	− 69	335	−1611
2050						
Increase	3044	3459	2945	3324	3260	1946
Decrease	2985	2560	3052	2672	2736	4083
Net	59	899	−107	652	524	− 2137
2085						
Increase	3316	3820	3303	3731	3728	2092
Decrease	3278	2757	3333	2803	2866	4478
Net	38	1063	−30	928	862	− 2387

5.2. *Effect of climate change on water resources stress*

By changing the amount of average annual runoff in and draining into a country, climate change will have an impact on water resources stress. Some countries will see an increase in the apparent water resource, but others will have a decrease.

Table 6 shows the change in numbers of people in countries using more than 20% of their resources, by 2025 ("2020s" climate), 2050 ("2050s" climate) and 2085 ("2080s" climate), relative to the "no climate change" reference case shown in Table 5. Another indicator of the effect of climate change is to calculate the difference between the number of people for whom climate change makes stresses worse and the number of people for whom climate change reduces stresses. Fig. 9 maps stressed countries (using more than 20% of their resources in the absence of climate change), and differentiates between those where stress is increased and those where it decreases (for just the HadCM2 GGax and HadCM3 scenarios). It also shows the countries which move into the stressed class due to climate change. Table 7 presents the difference between the populations in countries where climate change increases stress (countries already stressed plus those which move into the stressed class) and the population total in countries where climate change decreases stress.

By 2025, climate change increases the numbers of countries with water resources stress. The Ukraine, for example, uses more than 20% of its resources, and under HadCM3 so does the UK. The countries where climate change exacerbates water resources stress are in the Middle East, around the Mediterranean, in parts of Europe and in southern Africa. Countries in the southern Asia see increased stress under the HadCM2 scenarios, but a reduction in stress under HadCM3 (Fig. 9). The reduction in stress in India and Pakistan is the primary reason why the population seeing a reduction in stress exceeds the population suffering a decrease under HadCM3 (Table 7). China, along with other countries in southeast Asia, also sees a reduction in stress under the HadCM2 and HadCM3 scenarios. Under HadCM2, around 2.7 billion people will live in countries with an increase in water resources, offset by 2.4 billion living in countries with a reduction in stress. Under HadCM3, 1.8 billion will be living in countries with increased stress — but stress will be reduced for nearly 3.4 billion.

By 2050, there is a reduction in the population exposed to water resources under each of the HadCM2 scenarios, but an increase under HadCM3. This is because some high-population countries move out of the stressed class (the UK and, under GGa3, the USA) but relatively low population countries (Zimbabwe and, for GGa1 and GGa2, Greece) enter. Under HadCM3, no countries leave the stressed class, so the population at increased risk of water shortage increases. As in 2025, countries in southern Africa, north Africa, around the Mediterranean, in the Middle East and parts of Europe see an increase in water resources stress, whilst countries in southern and eastern Asia (including China) and, for the HadCM2 scenarios at least, the USA, see a reduction in stress. The apparent impacts of HadCM2 and HadCM3 are reversed when looking at the difference between the populations with an increase and decrease in stress, due to the different impacts of climate change in a number of populous countries.

By 2085, climate change under all the HadCM2 scenarios considered increases the net number of people in countries using more than 20% of their resources. Countries in southern Europe and southern Africa move into the stressed class, and only two low-population countries move out. The geographic distribution of the direction of change in stress is the same as in 2025 and 2050: southern Africa, the Middle East, and around the Mediterranean show an increase in stress, but southern and eastern Asia tend to show a reduction. Under the HadCM3 scenario, the USA experiences an increase in stress, but the countries of the Indian subcontinent see a reduction in stress: the apparent improvement in the position of these

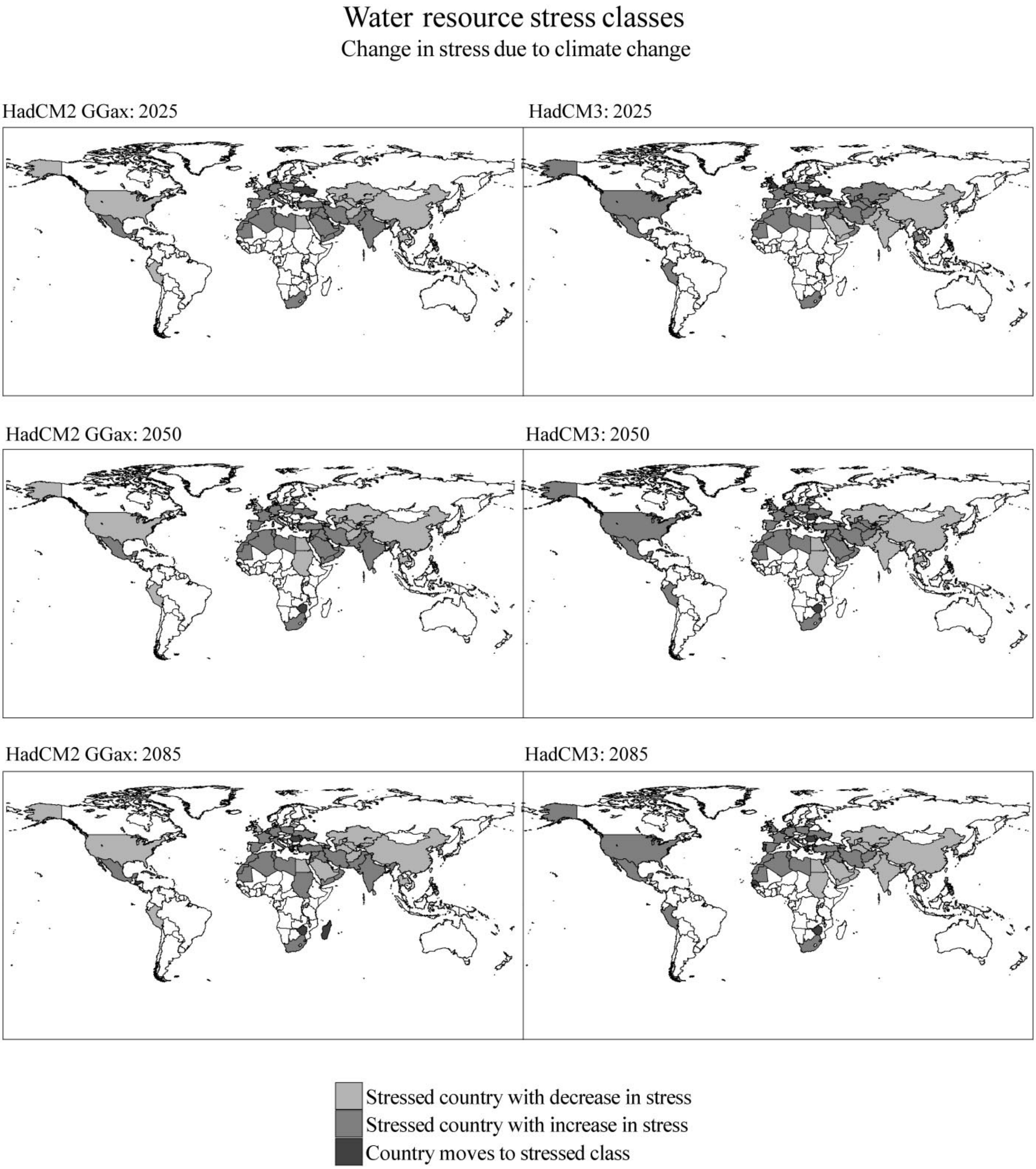

Fig. 9. Change in stress due to climate change, by 2025, 2050 and 2085, under the HadCM2 GGax and HadCM3 scenarios: stressed countries use more than 20% of available resources.

countries means that the total number with an increase in stress is outweighed by the total number with a reduction in stress under HadCM3.

The range in estimates of the effect of climate change between scenarios illustrates the sensitivity of estimated impact to scenario. Also, the average climate change (GGax) does not produce an average estimate of the impacts of climate change on water resources (when compared to the ensemble members), even though the hydrological change from GGax is close to the average.

Table 8
Numbers of people in countries using more than 20% of their resources by 2025, under three use scenarios and six climate change scenarios

	HadCM2						HadCM3
	No climate change	GGa1	GGa2	GGa3	GGa4	GGax	GGa1
Low	4907	3436	3488	4907	3436	3436	3488
Mid-range	5022	5022	5074	5074	5022	5074	5135
High	5146	5074	5135	5135	5135	5135	5146

Table 9
Change in number of people (millions) in countries using more than 20% of their resources by 2025, relative to the reference case (Table 4): three water withdrawal scenarios

	HadCM2					HadCM3
	GGa1	GGa2	GGa3	GGa4	GGax	GGa1
Low	− 1471	− 1419	0	− 1471	− 1471	− 1419
Mid-range	0	53	53	0	53	113
High	− 72	− 11	− 11	− 11	− 11	0

This is because of the nature of the impact indicator: it is based on class boundaries, and small differences in hydrological change can produce very substantial apparent changes in impact.

5.3. *Effect of demand uncertainty*

The figures and tables in the previous section have indicated the range in possible impacts of climate change on global water resources, arising just from different patterns of change in hydrology resulting from different climate model simulations. But the demand for water is also uncertain. This is partly because projections of population growth have wide ranges, and partly because estimates of future water use per capita are uncertain.

As noted earlier, the CDS developed not only a "mid-range" projection for future water withdrawals, but also a high and low projection. These were based on the same population projections, but on different — feasible — assumptions about patterns of future water use.

Table 8 shows the number of people in countries using more than 20% of their resources, under the low, mid-range and high water use scenarios, and the six climate change scenarios. Table 9 shows the difference from the reference case for each scenario, and Table 10 shows the numbers of people with an increase and a decrease in stress. It is clear that, although the number of people in stressed countries in the absence of climate change increases as the demand scenario changes from low to high, the effect of climate change is very variable: indeed, the mid-range scenario does not necessarily produce an estimate of impact between the low and high values. This is because the reference case has changed with different water use scenarios, and therefore different numbers of countries move in and out of stressed classes. The Phillipines, for example, moves out of the stressed category (using more than 20% of resources) under the low withdrawal scenario, for example, but under the high withdrawal scenario the UK, the Ukraine and Tajikistan move into the stressed class. However, under most climate change scenarios, the Ukraine and Tajikistan move out of the stressed class — and the net effect of climate

Table 10
Numbers of people with an increase and decrease in water stress due to climate change by 2025: three water withdrawal scenarios

	HadCM2					HadCM3
	GGa1	GGa2	GGa3	GGa4	GGax	GGa1
Low						
Increase	2439	2420	2477	2362	2652	1586
Decrease	2468	2540	2430	2545	2255	3373
Net	−29	− 120	46	− 184	398	− 1787
Mid-range						
Increase	2554	2420	2529	2476	2705	1762
Decrease	2468	2654	2545	2545	2369	3373
Net	86	−235	−16	−69	335	− 1611
High						
Increase	2554	2420	2529	2529	2705	1773
Decrease	2592	2726	2617	2617	2441	3373
Net	− 39	−306	−88	−88	264	− 1600

change is therefore to see more people move out of stress than under the mid-range scenario. Table 8 shows the numbers of people in stressed countries with increases or decreases in stressed (compare with Table 5). Again, the mid-range scenario does not always lie between the low and high withdrawal scenarios. Under a low withdrawal scenario, some countries become less sensitive to climate change (when impact is expressed in terms of a threshold exceedance), whilst under mid and high scenarios different groups of countries approach critical thresholds.

This analysis has demonstrated the sensitivity of estimates of climate change impacts to one aspect of the socio-economic scenario — change in water use per person, and has shown that the estimated impact of climate change is very dependent on the assumed socio-economic scenario. The additional effects of different population projections would lead to still greater variation.

6. Conclusions

6.1. Introduction

Over the next few years, an increasing population and increasing use of water will put increasing pressure on global water resources: pressures will increase most rapidly in Africa and parts of southern Asia. Climate change has the potential to exacerbate water resource stresses in some areas, but ameliorate them in others. This paper describes an assessment of the effects of climate change — as simulated by two Hadley Centre climate models — on hydrological regimes and water resources stresses at the global level. The climate change impact on water resources has been shown to be very sensitive to the climate change scenario, to the water demand scenario, and also to the precise definition of water resource stress.

6.2. Changes in hydrology

Although global average precipitation increases with climate change, much of this increase occurs over oceans and large parts of the land surface will experience a reduction in precipitation. This, coupled with the increase in evaporative demand associated with higher temperatures, means that river runoff would decrease across large parts of the world. At the global scale, there is little net change in total land surface runoff with the HadCM2 scenarios, but a reduction under HadCM3. In general, runoff increases in high latitudes, equatorial Africa and Asia, and southeast Asia. Under the HadCM2 scenarios runoff increases also across much of North America, but under HadCM3 large parts of North America see a reduction in runoff. Runoff generally declines in the mid-latitudes and sub-tropics. The four HadCM2 ensemble members produce generally similar changes in runoff, but the HadCM3 scenario often lies outside the range of the HadCM2 scenarios. This partly reflects the different distribution of precipitation change, but is also because the change in potential evaporation under HadCM3 is generally higher than under HadCM2.

The rise in temperature under each scenario leads to a general reduction in the proportion of precipitation that falls as snow (although increases in total precipitation may increase the total volume of snow) and the duration of snow cover. By the 2050s, the spatial extent of snow cover by the end of March (towards the end of the boreal winter) is considerably smaller than at present, under all scenarios, particularly in northern America and eastern Europe. This change in winter precipitation patterns has a significant effect on river flow regimes in these areas, with a widespread reduction in the spring snowmelt peak and an increasing concentration of flow during winter.

The study also looked at an index of high flows — the monthly maximum runoff with a return period of 10 years — and showed that this increased across much of the world, largely in parallel with the change in annual runoff (although the percentage increase was greater). An index of low flows — the annual minimum runoff with a return period of 10 years — was also calculated, and this too varied with the change in annual average runoff.

6.3. Changes in water resource stress

In the absence of climate change, around 5 billion people by 2025 will be living in countries using more than 20% of their water resources. Under the HadCM2 ensemble mean scenario, this figure would increase by 53 million, and under HadCM3 would rise by 113 million. However, by 2050 there would be a net reduction in populations in stressed countries under HadCM2 (of around 69 million), but an increase of 56 million under HadCM3. The lack of "smooth" progression reflects the variation in strength of climate change signal from 2025 to 2050, and also differences between the rate of growth of water use and the rate of change in water availability.

Another indicator of the effect of climate change on water resource stress is the difference between the number of people in stressed countries (using, for example, more than 20% of their resources in the absence of climate change) with an increase in stress minus the number of people in stressed countries with a decrease in stress, plus the number of people in countries which become stressed due to climate change. Under the HadCM2 ensemble mean scenario, there are 335 million, 524 million and 862 million people at increased risk of water shortage by 2025, 2050 and 2085, respectively. Under the HadCM3 scenario, however, the reduction in pressures in the Indian subcontinent mean that considerably more people apparently benefit from climate change in terms of reduced water stress.

The countries where climate change has the greatest adverse impact on water resources stress are located around the Mediterranean, in the Middle East and southern Africa. These countries are generally least able to cope with changing water resource pressures.

There is considerable difference in estimated impact between the different climate change scenarios used, with the HadCM3 results often lying outside the range of the HadCM2 results. The study showed that different indications of the impact of climate change on water resource stresses could be obtained using different projections of future water use. In fact, the analysis showed that the estimated impact of climate change with a mid-range water use scenario was not necessarily within the range of the estimated impacts under low and high water use scenarios: this is because the reference case is also different, and differing rates of change in water use change the geographic pattern of sensitivity to climate change. Also, the study used just one GCM (albeit several experiments made with it) and one greenhouse gas forcing scenario (1% compound per year).

6.4. Caveats and future extensions

The analysis exposed many difficulties with the definition of appropriate indices of water resources stress. Whilst it is possible in principle to determine a "stressful" threshold of water use (such as 20% of available resources), there may be significant changes in population totals deemed to be suffering water stress as large countries move across the threshold: a number of very populous countries (including China, the United States, India and Pakistan) are close to the 20% threshold, and small changes in resource availability in these countries can have very big impacts on estimated populations at risk from water shortage. This is an inherent weakness of a threshold-based impact indicator.

Also, climate change may lead to improvements in resource availability in some countries, offsetting deteriorations elsewhere. One measure of "impact" is therefore the net effect, or the difference between those in countries with a deteriorating position and those where water resource stresses should ease. However, this implicitly assumes that a "beneficial" impact exactly offsets an "adverse" impact, both within and between countries. A more sophisticated index might therefore weight "improvements" and "deteriorations" differently, perhaps according to capacity to adapt.

Part of the problem with the estimation of global water resource impacts lies in the selection of the national scale as the unit of analysis, but this is very much constrained by the availability of sub-national-scale water use data. Assessments at a smaller spatial scale would be less prone to major changes as populous countries move from one side of a use threshold to another, and would also allow different parts of large countries to be differently affected by climate change: the change in resource availability in the parts of a country with the greatest demand may be different to the change in national average resources.

More fundamentally, the impact index used (total water use over total water availability) assumes that water resource pressures are essentially a function of the total available resource. Whilst this gives a "macro-scale" perspective, in practice many water resource stresses relate to access to water *within* a basin. The impact index used probably understates the presence of water resource stresses in many developing countries with limited rural water distribution systems, particularly where a large proportion of the resources apparently available are concentrated in a narrow river corridor.

Two sets of refinements to the study are currently in hand. Refinements to the assessment of the hydrological effects of climate change include the incorporation of land cover change and an evaluation of the potential maximum effect of direct CO_2 enrichment. Refinements to the assessment of water resources impacts, largely triggered by the analysis presented herein, include calculating water resource pressures at the watershed, rather than national level, incorporating the effects of climate change on the demand for water (particularly irrigation), and the development of more refined indicators of the impact of climate change.

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