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Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines

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Abstract

This paper describes the way in which the socio-economic projections in the SRES scenarios were applied in a global-scale assessment of the impacts of climate change on food security, water stresses, coastal flood risk and wetland loss, exposure to malaria risk and terrestrial ecosystems. There are two key issues: (i) downscaling from the world-region level of the original scenarios to the scale of analysis (0.5° × 0.5°), and (ii) elaborating the SRES narrative storylines to quantify other indicators affecting the impact of climate change. National estimates of population and GDP were derived by assuming that each country changed at the regional rate, and population was downscaled to the 0.5° × 0.5° scale assuming that everywhere in a country changed at the same rate. SRES scenarios for future cropland extent were applied to current baseline data, assuming everywhere within a region changed at the same rate. The narrative storylines were used to construct scenarios of future adaptation to the coastal flood risk and malaria risk. The paper compares the SRES scenarios with other global-scale scenarios, and identifies sources of uncertainty. It concludes by recommending three refinements to the use of the SRES scenarios in global and regional-scale impact assessment: (i) improved disaggregation to finer spatial resolutions, using both "downscaled narrative storylines" and new technical procedures, (ii) explicit consideration of uncertainty in the population, GDP and land cover characterisations of each storyline, and (iii) use of a wider range of future socio-economic scenarios than provided by SRES if the aim of an impact assessment is to estimate the range of possible future impacts.

Keywords: Socio-economic scenarios; SRES; Climate change impact assessment; Population; Land use change

1. Introduction

The effects of human activities on climate depend on future emissions of greenhouse gases, and the impacts of the resulting changes in climate depend on the future state of the world. In 1990 and again in 1992 the Intergovernmental Panel on Climate Change (IPCC) developed emissions scenarios, which were subsequently widely used to drive climate models and determine the impacts of climate change. The IS92 family of scenarios (Leggett et al., 1992) was particularly widely used. Each emissions scenario corresponded to a particular set of assumptions about future population totals, economic development and land use change. However, the scenarios were not constructed with impacts assessments in mind, and little attempt was made by the impact assessment community to ensure that the socio-economic and demographic worlds being impacted by climate change were consistent with the worlds used to construct the emissions scenarios. For the IS92a scenarios, the work described by Parry and Livermore (1999) managed to find socio-economic scenarios that were broadly consistent with the IS92a 'world', but no direct IS92a source was available. More generally, few impact assessments have considered seriously the effect of changing socio-economic conditions on the impacts of

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future climate change (Berkhout and Hertin, 2000; Berkhout et al., 2002): see Parson et al. (2003) for a discussion of the difficulties involved in using socio-economic scenarios in the US National Assessment.

By the mid-1990s improvements in the understanding of many of the processes leading to the emission of greenhouse gases led to the development of a new set of scenarios. These were published in 2000 in the IPCC's Special Report on Emissions Scenarios (IPCC, 2000), and are termed the SRES scenarios. They contain more recent driving force data for emissions than the IS92 family of projections, and were constructed in a fundamentally different way. The starting point for each projection was a narrative "*storyline*", describing the way world population, economies and political structure may evolve over the next few decades. Four storylines were defined, and for each storyline several emissions scenarios were constructed, producing four "scenario families". Ultimately, six SRES *marker scenarios* were defined (one of the families has three marker scenarios, the others one each), and climate modellers agreed to use some or all of these six marker scenarios to drive their climate models to develop a series of comparable climate scenarios.

The SRES storylines, however, provide more than just input drivers to climate models. They represent a diverse range of different development pathways for the world which provide a meaningful basis for impact estimates. To provide the most consistent impact estimates, the climate associated with a given marker scenario should be superimposed onto the evolving demographic, socio-economic and political characteristics of the storyline that drives that marker scenario. In order to do this in practice, however, the narrative storylines and their associated generalised quantitative descriptors need to be downscaled to the spatial and temporal scales relevant to impact assessments: they were developed at the level of major world regions.

Most analyses of the SRES scenarios have focussed on mitigation of greenhouse gas emissions (Metz et al., 2001; Kainuma et al., 2003). There have been a small number of impact assessments (e.g., Berthelot et al., 2002) that have used the climate changes resulting from the SRES emissions scenarios, but very few that have also used the corresponding socio-economic scenarios. This is largely because the SRES storylines have generally not been characterised at scales appropriate for impact assessments or in terms of relevant indicators.

One exception is in the UK, where a set of socio-economic scenarios consistent with the SRES storylines (the UKSES scenarios: UKCIP, 2001) have been defined at the national scale. These four scenarios quantify changes in a number of indicators of the UK economy (see UKCIP, 2001; Berkhout et al., 2002). Two of these storylines were then further quantified and given spatial interpretations for a regional impact study in East Anglia and North West England (Shackley and Wood, 2001; Shackley and Deanwood, 2003). The results show that for some factors, socio-economic change is equally or more important than climate change (Holman and Loveland, 2001; Holman et al., in review). Parry et al. (2001) using the same UKCIP socio-economic scenarios combined with climate scenarios derived from HadCM3 (Johns et al., 2003) looked at the potential implications for UK agriculture and came to a similar conclusion.

However, it is easier to construct impact-oriented SRES socio-economic scenarios for a region than for the entire globe: regional scenarios need only be "consistent with" the SRES storylines,[1] but downscaled global scenarios need to be numerically identical to the driving global and world-region SRES characterisations.

The aim of this paper is to describe how the SRES storylines were characterised and applied at national and sub-national scales in order to assess the *global-scale* implications of changes in climate for food supply (Livermore et al., 2003), water scarcity (Arnell, 2003), malaria risk (Van Lieshout et al., 2003), coastal flood risk and wetland change (Nicholls, 2003), and terrestrial ecosystem change (Levy et al., 2003): the DEFRA "Fast Track" assessment. Some of this work was done on behalf of the IPCC's Task Group on Climate Impact Assessment (TGCIA), using the DEFRA "Fast Track" project as a test case (see Gaffin et al., 2003), and some was done by the Fast Track project group.

The next section describes the initial SRES storylines, and the subsequent sections describe the approaches used to characterise national and sub-national future population, national gross domestic product, and other important global-scale quantitative and qualitative socio-economic indicators used in the Fast Track project. The paper also briefly summarises the changes in climate simulated under the SRES emissions scenarios with the HadCM3 global climate model, used to provide the climate changes for the Fast Track project.

It is important to emphasise here that the SRES storylines represent just one of a number of global future socio-economic scenarios. UNEP's third global environmental outlook (GEO-3: UNEP, 2002), for example, uses four scenarios for the future—termed markets first, policy first, security first and sustainability first—which are different to the SRES storylines but have been numerically characterised in a similar way. They in turn are based on scenarios constructed for the Global Scenarios Group (www.gsg.com, Kemp-Benedict et al., 2002). Lastly, note that the SRES storylines do not necessarily encompass the full range of possible socio-economic futures, as this was not part of their

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[1] In other words, there is considerable scope for variation around the global SRES storyline narrative.

design: they explicitly do not, for example, include "disaster" scenarios.

2. The SRES storylines

The four SRES storylines represent different world futures in two dimensions: a focus on economic or environmental concerns, and global or regional development patterns (Fig. 1). The four storylines can be briefly characterised as follows (Table 1):

(A1) Very rapid economic growth with increasing globalisation, an increase in general wealth, with convergence between regions and reduced differences in regional per capita income. Materialist–consumerist values predominant, with rapid technological change. Low population growth. Three variants within this family make different assumptions about sources of energy for this rapid growth: fossil intensive (A1FI), non-fossil fuels (A1T) or a balance across all sources (A1B). Note that only the A1FI variant is considered in this analysis.

(A2) Heterogeneous, market-led world, with more rapid population growth but less rapid economic growth than A1. The underlying theme is self-reliance and preservation of local identities. Economic growth is regionally oriented, and hence both income growth and technological change are regionally diverse. Fertility patterns across regions converge slowly, resulting in high population growth.

(B1) Same low population growth as A1, but development takes a much more environmentally sustainable pathway with global-scale cooperation and regulation. Clean and efficient technologies are introduced. The emphasis is on global solutions to achieving economic, social and environmental sustainability.

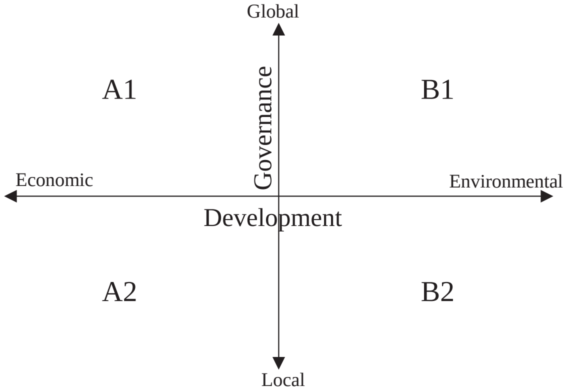

Fig. 1. SRES storylines.

(B2) Population increases at a lower rate than A2, with development following environmentally, economically and socially sustainable locally oriented pathways.

Broad quantitative indicators were specified by region for each of the four storylines (Table 1), and six different modelling groups used different integrated assessment models (and different regions) to translate these basic input data into emissions scenarios, making different sets of assumptions about other key variables. From the 40 scenario quantifications, six were subsequently selected as marker scenarios. The SRES report (IPCC, 2000) publishes quantitative indicators for four major world regions—OECD countries, the Former Soviet Union, Asia and the rest of the world (Africa and Latin America)—although as noted below many of these indicators were aggregated from a larger number of smaller regions.

3. Future populations

3.1. Construction of the original SRES scenarios

The integrated assessment models used to characterise the SRES scenarios all used population projections from both the UN and IIASA as input data.

A1 and B1 have the same population projections, based on the IIASA "rapid" fertility transition projection, which assumes low fertility and low mortality rates (Lutz, 1996). A2 is based on the IIASA "slow" fertility transition projection, with high fertility and high mortality rates (Lutz, 1996). The A1/B1 and A2 scenarios were constructed by IIASA on a regional scale from 1995 onwards, using 13 world regions: North Africa, Sub-Saharan Africa, China and Centrally Planned Asia, Pacific Asia, Pacific OECD, Central Asia, Middle East, South Asia, Eastern Europe, European part of the former Soviet Union, Western Europe, Latin America, and North America.

The B2 scenario was also developed to 2100 on a regional scale, but based on national-scale projections to 2050. The B2 scenario uses the UN 1998 "medium" Long Range Projection, which itself used an earlier UN national-scale projection to 2050. The "official" UN 1998 Long Range Projections were based on just eight regions, but high higher-resolution "unofficial" version was prepared specifically for the SRES scenarios for 11 regions. These regions are: North America, Western Europe, Pacific OECD, Central and Eastern Europe, Newly independent states of the former Soviet Union, Centrally planned Asia and China, South Asia, Other Pacific Asia, Middle East and North Africa, Latin America and the Caribbean, and Sub-Saharan Africa.

Table 1
SRES scenario quantifications (IPCC, 2000); numbers are for 2100

	Storyline			
	A1	A2	B1	B2
Population growth	Low ~7 billion	High ~15 billion	Low ~7 billion	Medium ~10 billion
GDP growth	Very high 525–550[a]	Medium 243	High 328	Medium 235
GDP per capita[b]	Ind.: US$107,300 Dev.: US$66,500	Ind.:US$46,200 Dev.: $11,000	Ind.: US$72,800 Dev.: US$40,200	Ind.: US$54,400 Dev.: US$18,000
Energy use	Very high/high	High	Low	Medium
Land use changes	Low-medium Cropland + 3% Forest + 2%	Medium-high —	High Cropland − 28% Forest + 30%	Medium Cropland + 22% Forest + 5%
Resource availability	High/medium	Low	Low	Medium
Pace and direction of technological change	Rapid	Slow	Medium	Medium
Favoured energy	Fossil/balanced/non-fossil	Regional diversity	Efficiency and dematerialisation	"Dynamics as usual"

Note: There are three variants of the A1 storyline, representing different energy uses.

[a] World GDP (trillion 1990 US$) in 2100.

[b] GDP per capita in 1990 US$, market exchange prices.

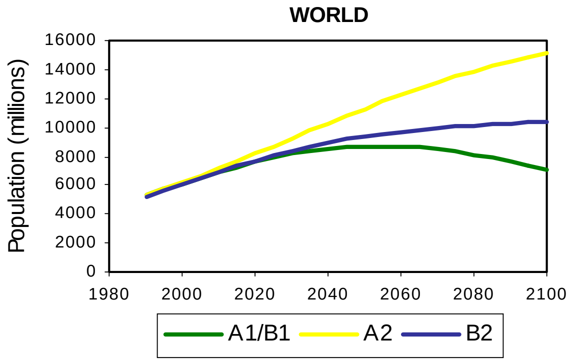

Fig. 2. Global population totals under the SRES scenarios.

These regions are different to those used to construct the A1/B1 and A2 population scenarios.

Fig. 2 shows the global population totals under each scenario.

3.2. Downscaling to the national level

The regional SRES population projections were downscaled to the national scale by the IIASA population project (A1/B1 and A2: Lutz and Goujon, 2002) and CIESIN (B2: CIESIN, 2002a): slightly different approaches were used, as described in detail in Gaffin et al. (2003).

The downscaling from region to country level for the A1/B1 and A2 scenarios used another set of population projections made by the UN Population Division (the UN 2000 projections) to 2050. For each SRES population scenario, the United Nations variant that was the closest to the SRES scenario was chosen as the starting point for the population downscaling. For scenarios A1 and B1 the UN 2000 medium variant was chosen: according to this variant the world population in 2050 will be 9.3 billion whereas the SRES A1/B1 scenarios estimated that population will be 8.7 billion in 2050. For scenario A2, the United Nations 2000 high variant was used. According to this variant, the world population in 2050 will be 10.9 billions whereas the A2 scenario gives a population of 11.3 billion in 2050.

The B2 scenario already includes national projections to 2050, and national estimates from 2055 to 2100 were made by assuming that the regional growth rates defined by the UN 1998 Medium Long Range Projection apply to all countries within a region. This is mathematically equivalent to assuming that a country continues to have the same fractional share of regional population.

With each downscaled projection there are some discontinuities between 2050 and 2055, due to the switch from national to regional growth rates. If a country's population changes at a different rate to the regional average, then there will be a discontinuity which may cause problems if time series of impacts are calculated. This is most likely for relatively small countries, and Fig. 3 gives an example.

The downscaling by CIESIN excluded 44 small countries with 1995 population less than 150,000,

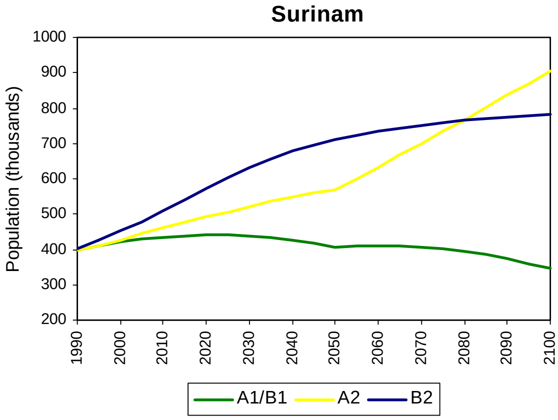

Fig. 3. Example of discontinuity in national population totals at 2050.

because the UN projections for these countries were not available in electronic form. For most global impacts, these small countries are negligible, but for coastal impacts many of them are critical as they are small island states in the Caribbean, Indian Ocean and Pacific Ocean which are highly vulnerable to sea-level rise (Nurse et al., 2001). Therefore, population scenarios were developed by the Fast Track group for these countries by calculating the regional trends for those larger countries in the region that had been downscaled by CIESIN and applying these regional trends to the smaller countries (Table 2).

The influence of preferential migration of population to the coast is also considered by Nicholls (2003) by considering two population scenarios. The first simply assumes uniform national change, but the second assumes that coastal population grows at twice the national growth (or half the national fall in cases of population decline).

3.3. Downscaling to 0.5° × 0.5°

The national populations were then downscaled to the 0.5° × 0.5° resolution using the Gridded Population of the World (GPW) Version 2 data set (CIESIN et al., 2000), which has a spatial resolution of 2.5 × 2.5′. This involved two stages.

First, the 2.5 × 2.5′ data (1995 "adjusted" data set) were rescaled using national ratios of future population to the 1995 population. This makes the key assumption that population changes everywhere within a country at the same rate. A more sophisticated approach would allow for differential growth rates between urban and rural areas.

Second, the population in each 0.5° × 0.5° grid cell was determined by summing the population in all the 2.5 × 2.5′ cells falling within the cell. An individual 0.5° × 0.5° cell can, of course, include smaller cells from more than one country.

Table 2
Small island nations and groups in the Caribbean, Indian Ocean and Pacific Ocean which required separate downscaling

Country/island group	Approach to develop population and GDP scenarios
Anguilla	Used regional Caribbean changes
Antigua and Barbuda	
Aruba	
British Virgin Islands	
Cayman Islands	
Dominica	
Grenada	
Montserrat	
St. Helena	
St. Lucia	
St. Vincent	
Turks and Caicos Islands	
Virgin Islands (US)	
Christmas Islands	Used regional Indian Ocean small island changes
Cocos (Keeling Islands)	
Mayotte	
Seychelles	
America Samoa	Used regional Pacific small island changes
Cook Islands	
Kiribati	
Marshall Islands	
Micronesia	
Nauru	
Niue	
Norfolk Island	
Northern Marina Islands	
Palau	
Pitcairn Island	
Tokelau	
Tonga	
Tuvalu	
Wallis and Futuna	

Fig. 4 shows the gridded population in 1995 and for 2055 under the A2 world, and illustrates the parts of the world with the greatest change in population. The maps for A1/B1 and B2 are very similar to that for A2, although the total populations are different.

4. Future economic growth

4.1. The original SRES scenarios

The economic growth rate is a key assumption in each SRES scenario family. Economic growth rates were assumed to be "very high" for the A1 family, "medium" for the A2 family, "high" for the B1 family and "medium" for the B2 family (IPCC, 2000). Quantitatively these assumptions translated into world GDP for

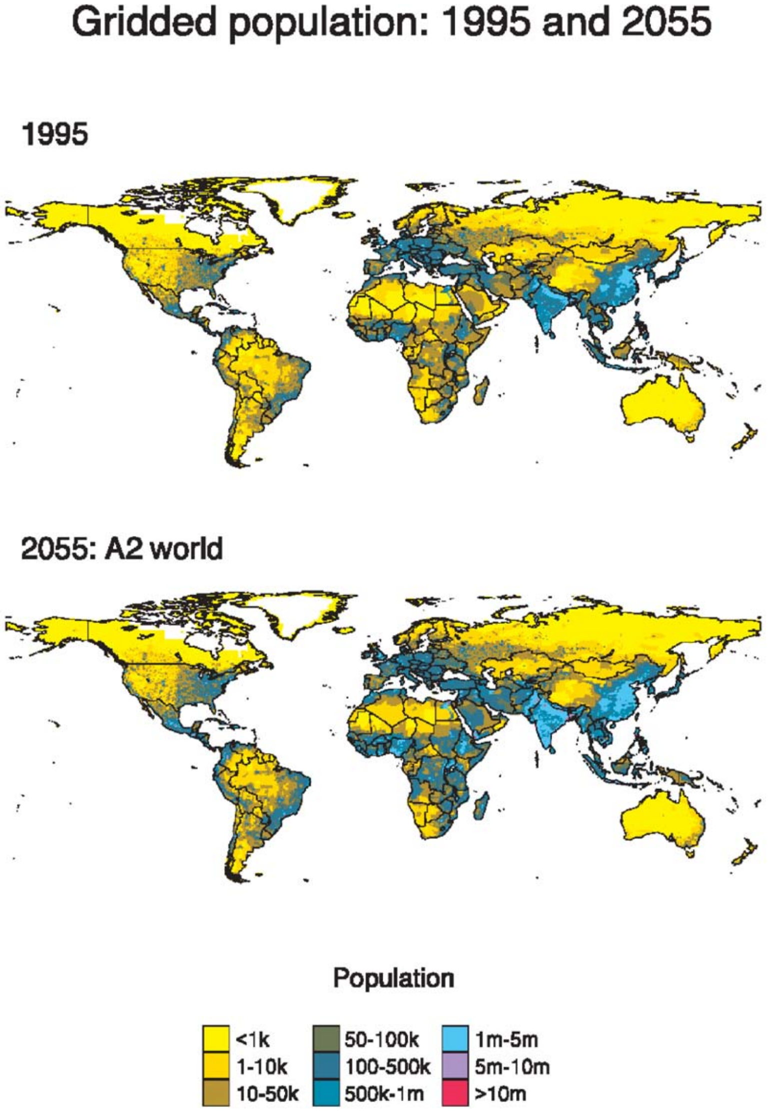

Fig. 4. Gridded future population: 1995 and 2055 (A2 world).

2100 of approximately 525–550 trillion US1990\$/year for the A1 family, 243 trillion US1990\$/year for the A2 family, 328 trillion US1990\$/year for the B1 family and 235 trillion US1990\$/year for the B2 family, with the precise amount depending on the integrated assessment model used to simulate economic changes.

Fig. 5a shows the rate of change of global GDP (assuming market exchange rate: $\mathrm{GDP}_{\mathrm{MER}}$). Per capita $\mathrm{GDP}_{\mathrm{MER}}$ growth rates depend, of course, on the assumed rate of population growth, and Fig. 5b shows per capita $\mathrm{GDP}_{\mathrm{MER}}$ (again in US1990\$) under the four SRES scenario families. Fig. 6 shows the per capita $\mathrm{GDP}_{\mathrm{MER}}$ for four world regions. It is also possible to compare and combine national GDP figures using Purchasing Power Parity (PPP). This reduces the difference between rich and poor countries, but estimates of future PPP depend very much on assumed future purchasing preferences in different countries.[2] The SRES authors therefore used $\mathrm{GDP}_{\mathrm{MER}}$ to determine emissions scenarios. Global and regional GDP estimates based on PPP were actually provided in the SRES report (IPCC, 2000) for the A1T and B2 marker scenarios (based on the MESSAGE integrated assessment model). There is little difference between $\mathrm{GDP}_{\mathrm{MER}}$ and $\mathrm{GDP}_{\mathrm{PPP}}$ after 2050, but before then the OECD countries are relatively less rich, and the rest of the world less poor, with $\mathrm{GDP}_{\mathrm{PPP}}$.

1990 was selected as the base year by the SRES authors because it is the most recent year with consistent high-quality data available at the national scale.

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[2] Note that the Global Scenario Group expressed GDP in PPP terms: they first assumed growth rates using MER, then applied assumed conversions between PPP and MER (Kemp-Benedict et al., 2002).

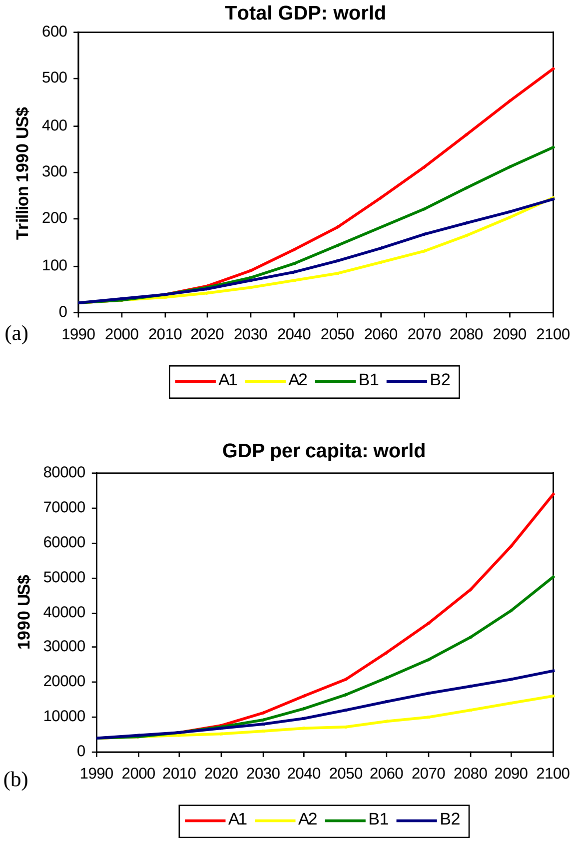

Fig. 5. Global GDP_{MER}: absolute (a) and per capita (b).

4.2. Downscaling to the national scale

National GDP_{MER} to 2100 was estimated by CIESIN (CIESIN, 2002b; Gaffin et al., 2003) simply by applying the regional change from 1990 to the national 1990 absolute GDP. Each country does not of course grow at the same rate, so the method leads to inaccurate projections over the short term. This is particularly significant where high income countries are located in regions with high growth rates: these include Singapore, Hong Kong, French Polynesia, New Caledonia, Brunei Darussalam, Renuion, Republic of Korea, Gabon, and Mauritius.

As with population, the downscaling by CIESIN excludes 44 small countries with 1995 population less than 150,000. For small island states in the Caribbean, Indian Ocean and Pacific Ocean, GDP_{MER} scenarios were developed using the same method as for the population. It is important to note that the different models used to estimate emissions under the SRES storylines grouped countries into slightly different regional groupings, and regional GDP_{MER} estimates are therefore not strictly comparable. For example, in the B1 storyline the Pacific Islands are linked to Australia and New Zealand, rather than Asia, leading to smaller estimates for GDP_{MER} growth than under the other storylines. The downscaling by CIESIN retained the regional groupings used for each storyline.

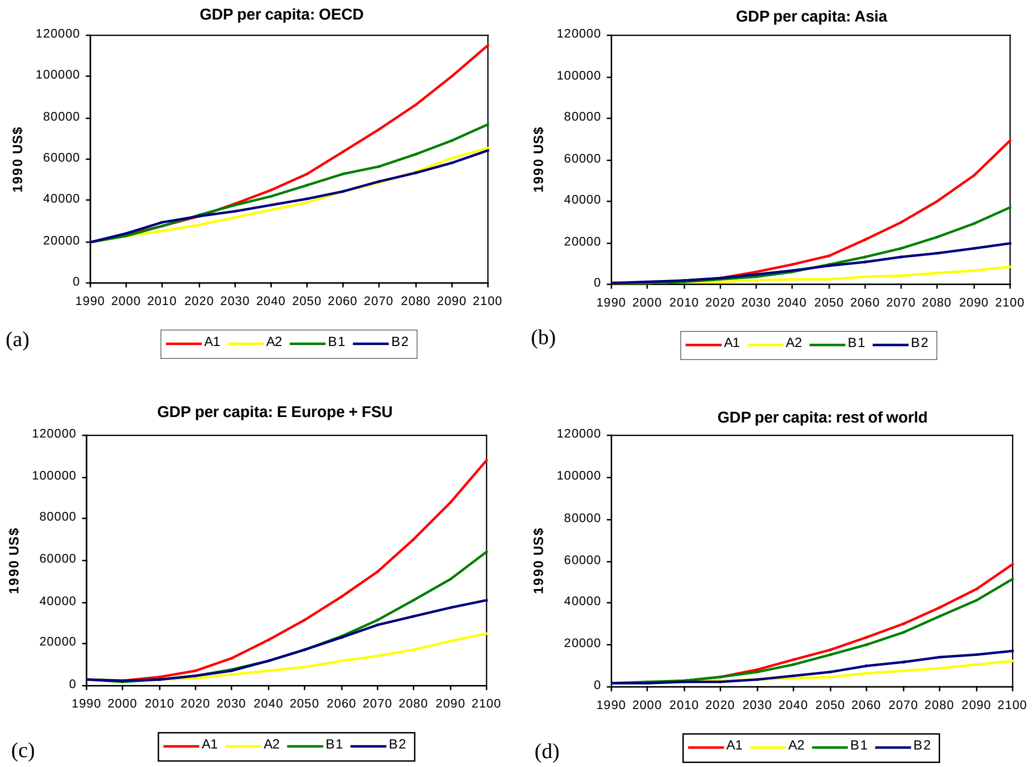

Fig. 6. Regional GDP_{MER} per capita.

The Fast Track project did not require GDP at finer than the national scale, so further downscaling was not implemented. One way of downscaling would have been simply to use the downscaled population to disaggregate national GDP (as done by Gaffin et al., 2003), but this assumes that economic productivity is directly proportional to population density.

5. Land cover

The Fast Track assessments of potential changes in terrestrial ecosystems, food supply and water stresses required data on future land cover: only the terrestrial ecosystems component used explicitly the published SRES land cover scenarios.

The HyLand terrestrial ecosystem model simulates the "natural" vegetation at each location as determined by climate, and previous applications of the model (White et al., 1999, 2000) assumed that present and future land cover is determined only by climate. A key refinement of the terrestrial ecosystem assessment (Levy et al., 2003) has been the inclusion of the agricultural land cover, and particularly changes in agricultural land cover over time. The terrestrial ecosystem model uses data on the extent of cropland and pasture in the past and future to "over-ride" the simulated natural vegetation cover. The historical cropland area data (Ramankutty and Foley, 1999) are available at 30-year time steps between 1770 and 1992 at a spatial resolution of $0.5^\circ \times 0.5^\circ$. The data show an increase in cropland from around 2% of the global land area in 1700, to over 13% in 1990. These data were averaged to the $3.75^\circ \times 2.5^\circ$ scale at which HyLand is applied (this is the scale of the driving climate model). The HyLand model actually works by simulating ecosystems at 10 different plots within each climate model grid cell, each with a discrete land cover type. At each time step, a proportion of the 10 plots is converted from the natural vegetation to cropland, via a clearcutting stage, consistent with the proportion of the grid cell covered by cropland.

The published SRES scenarios include changes in the areas of cropland, grassland, forest and energy biomass crop production for the four major SRES world regions. Land use was an output from most of the integrated assessment models used to characterise the SRES storylines, and projections for a given storyline are therefore model-dependent. For example, under the B2 storyline the change in the global area of grassland between 1990 and 2050 varies between -49 and $+628$ million ha (Mha) (IPCC, 2000). The land cover changes under the selected marker scenarios are therefore highly uncertain: the marker scenario for B2, for example, specifies a change in global grassland area between 1990 and 2050 of $+167$ Mha. Fig. 7 shows the change in global land cover from 1990 under the A1, B1 and B2 marker scenarios, together with estimates made using the other integrated assessment models: the differences are clearly large. The integrated assessment model used to characterise the A2 marker scenario did not include land cover change, so changes under the A1 scenario were assumed to apply also to A2. The SRES land cover scenarios do not include the effect of climate change on future land cover.

There are three issues in the application of these world-region projections to estimate future land cover. First, the observed area of cropland summed across each region is greater than the baseline value used in the SRES projections, and second, the SRES scenarios need to be downscaled to the scale of the ecosystem model. The SRES projections were therefore used to derive regional *trends* in cropland change, which were then applied to all the grid cells within a region to alter over time the proportion of the 10 plots assumed covered by cropland. This avoids the discontinuity between past and future, but does make the assumption that everywhere within a major world region changes at the same rate: in practice, land cover change is likely to be greatest where population and population growth rates are greatest. The third problem is that there is a mismatch between recent trends and projected future cropland change in two of the SRES storylines (Levy et al., 2003). The B1 and B2 scenarios project a decrease in cropland area and an increase in forest cover—which is consistent with the assumptions behind the scenarios but inconsistent with trends over the last century—and even the A1 scenario assumes that forest cover by the end of the 21st century will be similar to 1990.

The water sector study assumed that current land cover in each $0.5^\circ \times 0.5^\circ$ cell continued into the future, and that land cover was therefore affected by neither climate change nor other drivers of land cover change. This assumption was necessary because of the difficulties associated with downscaling both the SRES land cover scenarios (from the SRES regional scale) and the effects of climate change on land cover (from the climate model resolution) to the $0.5^\circ \times 0.5^\circ$ resolution.[3]

The food sector study also did not use explicitly the SRES land cover scenarios, because the area of cropland is an output from the food production model. To impose the SRES estimates on the basic linked system (BLS) world food trade model used to estimate prices would have restricted the normal behaviour of the model in its simulation of agricultural practices adapting to environmental pressures. Instead the model takes its land use parameters from the latest FAO estimates. Globally, it is estimated that ~3200 Mha are suitable for arable enterprises, of which ~1400 Mha is cultivated

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[3] High-resolution land cover scenarios are available from the IMAGE 2.2 integrated assessment model (IMAGE Team, 2001), but not with HadCM3 climate change patterns.

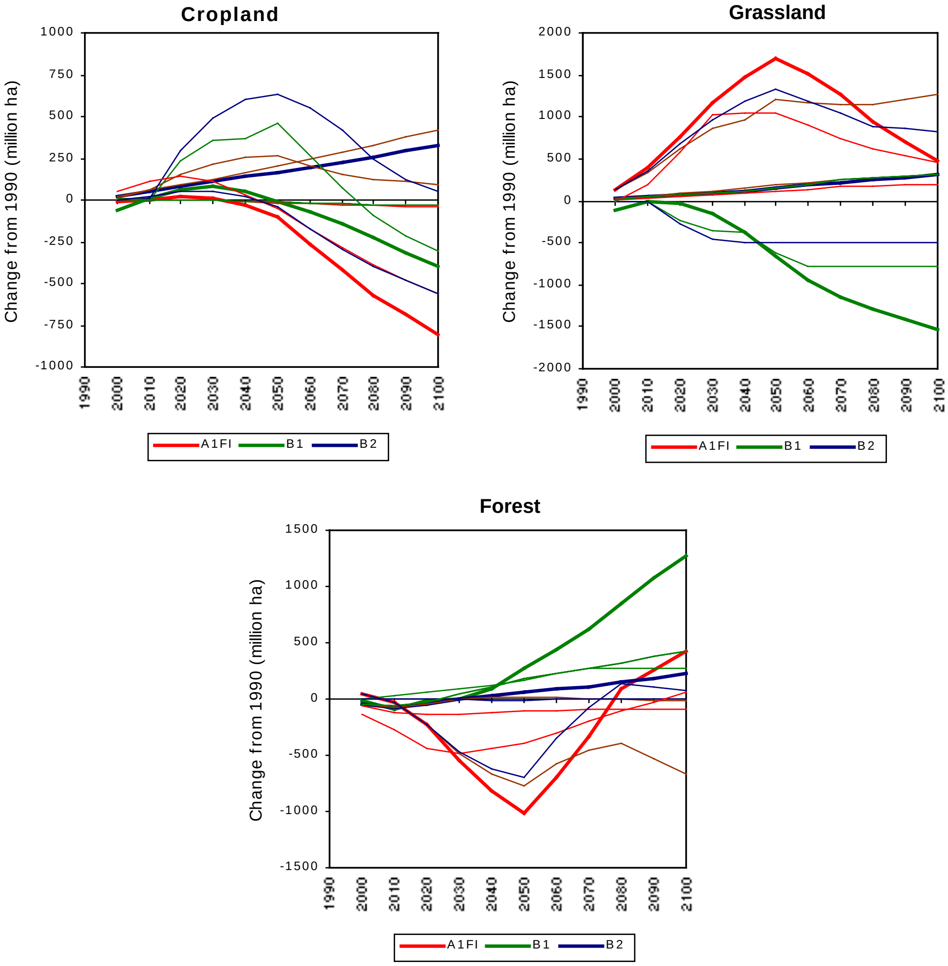


Fig. 7. Global land cover change under the SRES scenarios.

Table 3
Global cereal land area (defined as 50% of cropland) as specified in the SRES and used in the BLS (areas in Mha)

Year	BLS				SRES			
	A1FI	A2	B1	B2	A1FI	A2	B1	B2
1990s	747	746	747	746	736	730	718	730
2020s	872	875	874	880	744	784	754	777
2050s	928	995	918	947	644	841	697	821
2080s	972	1091	939	995	422	905	583	867

with cereal production accounting for 680 Mha, or nearly 50% of the total cultivated land (FAO, 2002). With this starting point, the BLS standard national models employ a piecewise linear time-trend function to impose upper bounds (inequality constraints) on land use. In addition, this time-trend function is modified with an elasticity term (usually 0.05 or less) that reacts to changes in shadow prices of land in comparison to 1990 levels. The upper limits imposed by the time-trend function utilise the FAO data on potential arable land. However, this is not a perfect solution as the arable land limits are not adjusted due to climate change, even though they may be affected positively in some locations by extension of season length or drying of wet soils or negatively, by sea-level inundation or desertification. This leads to some significant differences between the BLS estimates and those published in the IPCC SRES. This is particularly evident in the B1 world where the BLS suggests a steady increase in arable land use throughout the 21st century while the SRES suggests a decrease in cropland after the 2020s (Table 3).

6. Elaborating the SRES narratives

The previous sections have described how quantitative regional data included within the SRES scenarios were downscaled to the national or sub-national level. The SRES storylines also contain detailed narrative information which can help in the construction of other useful quantitative and qualitative scenarios, including characterisations of potential adaptive responses to climate change. These narrative descriptions have so far been used to produce further quantitative indicators at the sub-national and national level (as in the UK: Shackley and Wood, 2001; Shackley and Deanwood, 2003; UKCIP, 2001), but the Fast Track study required these elaborations at the global scale. The ability of institutions to adapt to climate-related threats is also likely to vary between the SRES storylines, and the SRES report (IPCC, 2000) describes some of the differences in potential environmental policies between the storylines: the European ACACIA report (Parry, 2000) rephrased these for the European Union, and the UKSES scenarios (UKCIP, 2001; Berkhout et al., 2002) inferred policy preferences at the national level for the UK.

The exposure of human populations to coastal flooding depends primarily on the size of the coastal population and coastal defence policy, while the magnitude of relative sea-level rise will depend on the magnitude of coastal subsidence. Table 4 summarises how coastal population and subsidence vary with the SRES storylines and this is then used in the interpretation of the impact modelling of coastal flooding (Nicholls, 2003). The A1/B1 worlds are more globalised worlds with free movement of people, so that population growth in coastal areas would be expected to be higher than in the more heterogeneous, locally focussed B2/A2 worlds. The A1/A2 worlds are more individualistic and hence ad hoc groundwater withdrawal to supply local water needs is more likely than in the B1/B2 worlds, where community values and regulations have a greater influence. Groundwater withdrawal can lead to enhanced land subsidence in the appropriate geological settings. Nicholls (2003) similarly argued that direct and indirect human pressure on coastal wetlands will be much greater in the A1/A2 worlds than the B1/B2 worlds due to the lower value placed on the environment in the former two storylines.

Table 4
Qualitative assessment of some issues relevant to coastal flooding for each SRES storylines (population change and human influence on subsidence)

“A1 world”	“B1 world”
Coastal population change: higher Human-induced subsidence: more likely	Coastal population change: higher Human-induced subsidence: less likely
“A2 world”	“B2 world”
Coastal population change: lower Human-induced subsidence: more likely	Coastal population change: lower Human-induced subsidence: less likely

The GDP/capita scenarios are used to estimate the future standards of coastal defences in the absence of relative sea-level rise (i.e., evolving protection scenarios) by Nicholls (2003). In general the scenarios appear quite robust, although the regional groupings do differ with the underlying model used for each marker. The B1 case used the IMAGE emissions model and the Pacific islands are regionally grouped with Australia and New Zealand (rather than with Asia as in the other markers). As the Australian and New Zealand economies dominate, so the Pacific islands are projected to experience much more limited growth than under the A1 and B2 scenarios, which does not appear entirely consistent with the storylines. In the flood analysis, both Large Pacific Islands and Small Pacific Islands appear more vulnerable under the B1 scenario due to this effect. Any future scenario exercises for impact assessments should ideally be based on common regions to avoid this effect.

In the health assessment, the SRES scenarios are interpreted qualitatively in relation to future national capacity to control malaria. The economic scenarios were not directly included in the model due to the lack of a reliable economic indicator for malaria burden. The relationship between GDP and malaria burden is confounded by environmental and climate factors. Assumptions about the priority of public health in the future under each storyline can be made, as for environmental policies. Investment in the public health infrastructure, both within and between countries, would be expected to be greater in B1/B2 worlds.

The food model used to estimate future risk of hunger makes assumptions about yield changes, food demands and trade liberalisation. Technical yield changes are assumed the same as in previous work (Parry et al., 1999) and are held constant across all storylines. Table 5 documents the difference in assumed yield trends presented in the SRES compared to those used within the BLS modelling framework. According to FAO data, yields during the period 1961–1990 have been growing at an average of around 2.5% annually. However, the 1990s has seen a dramatic downturn in yield growth rates with current statistics suggesting a less than 1% per annum increase in yields throughout the decade (FAO, 2002). This is not reflected in the SRES figures. The falling growth rates utilised in the BLS may be justified for several reasons. Historical trends suggest decreasing rates of increase, and yield improvements from biotechnology have yet to be realised. Much of the large yield increases in developed countries in the 1950s and 1960s

Table 5
Summary of technological yield changes (% per annum) specified in the SRES, compared to those used in the BLS

	BLS				SRES			
	A1	A2	B1	B2	A1	A2	B1	B2
Global	1.2	1.2	1.2	1.2	1.5	—	2.0	1.0
Developed	1.0	1.0	1.0	1.0	—	1.0	—	1.0
Developing	1.7	1.7	1.7	1.7	—	1.5	—	1.0

Table 6
Global CO_2 concentrations (ppmv) used in the SRES-driven HadCM3 climate change experiments

	IS92a	A1FI	A2	B1	B2
1990s	334	358	358	358	358
2020s	433	432	432	421	422
2050s	527	590	549	492	488
2080s	642	810	709	527	561

Table 7
Summary of projected changes in global mean temperatures (°C), relative to the 1961–1990 mean

Year	IS92a	A1FI	A2a	A2b	A2c	B1	B2a	B2b
2020s	1.10	0.99	0.86	0.93	0.88	0.84	0.91	0.91
2050s	2.06	2.26	1.92	1.89	1.85	1.45	1.56	1.66
2080s	3.00	3.97	3.21	3.28	3.32	2.06	2.35	2.40

Note: IS92a values come from HadCM3GGa1 experiment described in Hulme et al. (1999).

and in developing countries thereafter has been due to intensification of chemical inputs and mechanisation. Apart from economic reasons and environmental concerns which suggest that maximum input levels may have been reached in many developed countries, there are likely to be diminishing rates of return for further input increases. In some developing countries, especially in Africa, increase in input levels and intensification of production are likely to continue for some time, but may also ultimately level off meaning that further increases in agricultural productivity will have to come through the expansion of land under cultivation.

A similar assumption is made about trade liberalisation as the SRES storylines contain little quantitative information that could be used as input to the BLS. Demand for food, however, is allowed to vary between scenarios as it is linked to per capita GDP.

7. Climate change scenarios

The quantified SRES emission scenarios have subsequently been used as inputs to climate change experiments conducted by several modelling groups (Dai et al., 2001; Flato and Boer, 2001; Johns et al., 2003; Noda et al., 2001; Nozawa et al., 2001; Stendel et al., 2000; Washington et al., 2000). Most groups have focused on the A2 and B2 scenarios. One noticeable exception, chosen to supply the climate inputs to the Fast Track project, is the UK Hadley Centre which has conducted at least one experiment for each SRES marker scenario (A1FI, A2, B1 and B2). Further information regarding the HadCM3 experiments, including a discussion of results from these experiments and a comparison with an earlier IS92a experiment also conducted with HadCM3 can be found in Johns et al. (2003). The data from these experiments are now available through the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk).

While the use of climate scenarios from one model means that uncertainties due to model structure cannot be investigated, the availability of a full and consistent range of SRES climate scenarios allows for the examination of a wider range of future climate outcomes to be examined in the context of as wide a range of socio-economic development pathways as possible.

Table 6 details the atmospheric CO_2 concentrations for the 2020s, 2050s and 2080s. Table 7 summarises the resulting changes in mean global temperatures for the three time slices. The effect of the different emissions scenarios clearly does not begin to manifest itself before the 2050s when the A1FI and A2 worlds begin to exhibit a significantly faster rate of warming than say the B1 world. As expected the A1FI world with the highest concentrations of atmospheric CO_2 is the warmest having witnessed an ~4°C increase in global mean annual temperatures with regional increases in excess of 8°C by the 2080s. In contrast the B1 scenario witnesses just over a 2°C increase over the same time period with the A2 and B2 experiments falling somewhere in between.

The Fast Track project has also made use of two ensemble experiments conducted with HadCM3 providing two additional A2 projections and one B2-based projection. This brings the total number of identified climate projections to seven. Looking at the global averages, variations between ensemble members tend to be smaller than the variation between different scenarios suggesting that the climate change pattern is relatively stable between integrations. However, subtle regional differences are evident as demonstrated in Figs. 8 and 9. For example, comparing the A2a and A2c experiments there is a marked difference in the increase in annual temperatures over the North Atlantic and Arctic regions, A2c being several degrees warmer in places. Striking differences are also present in the precipitation fields, one example being over India where the A2a

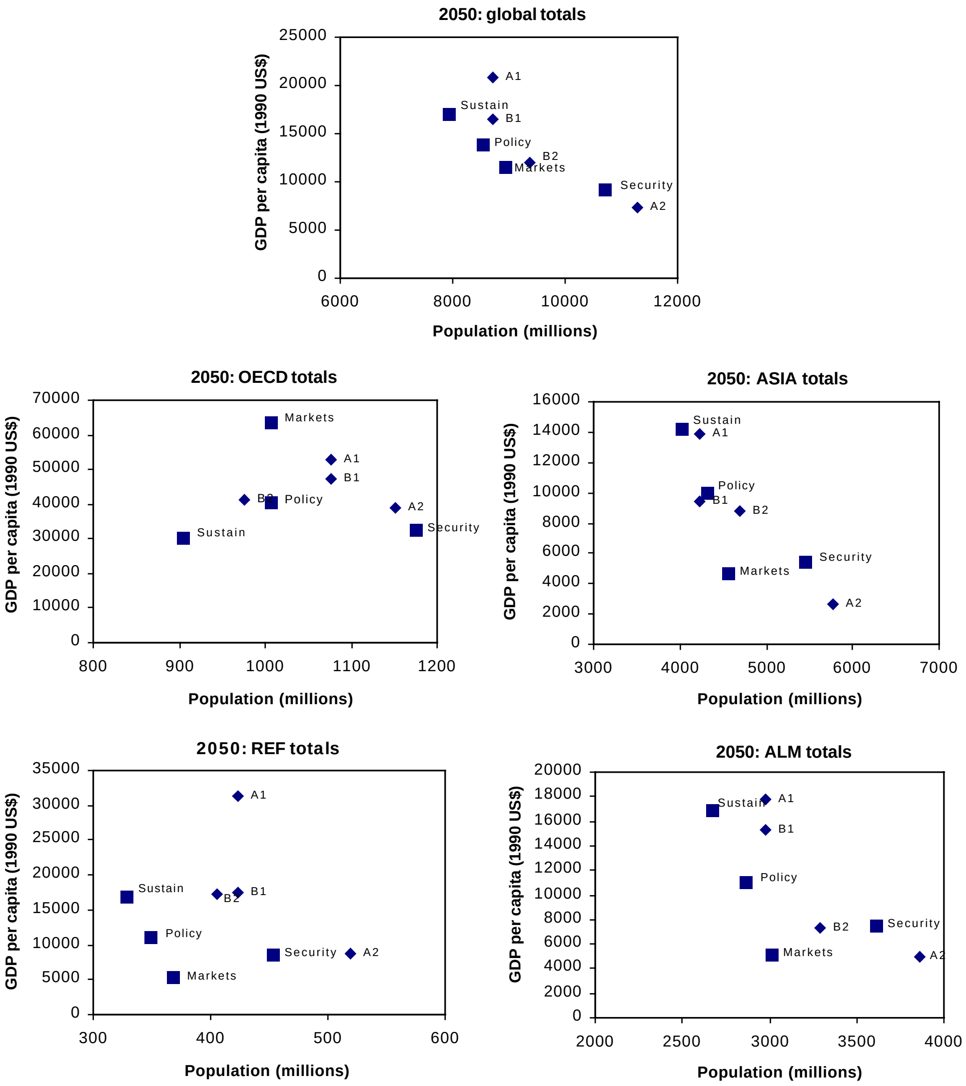


Fig. 8. Population and GDP_{MER} per capita under the four SRES scenarios and four GEO-3/GSG scenarios, by 2050, for the world and four major world regions.

scenario suggests a drying while A2b suggests an increase in precipitation. The use of the ensemble experiments allows several of the sectoral studies, notably food, human health and water, to assess the influence of multi-decadal variability and uncertainties in the regional manifestation of the climate change signal on estimates of future global impacts.

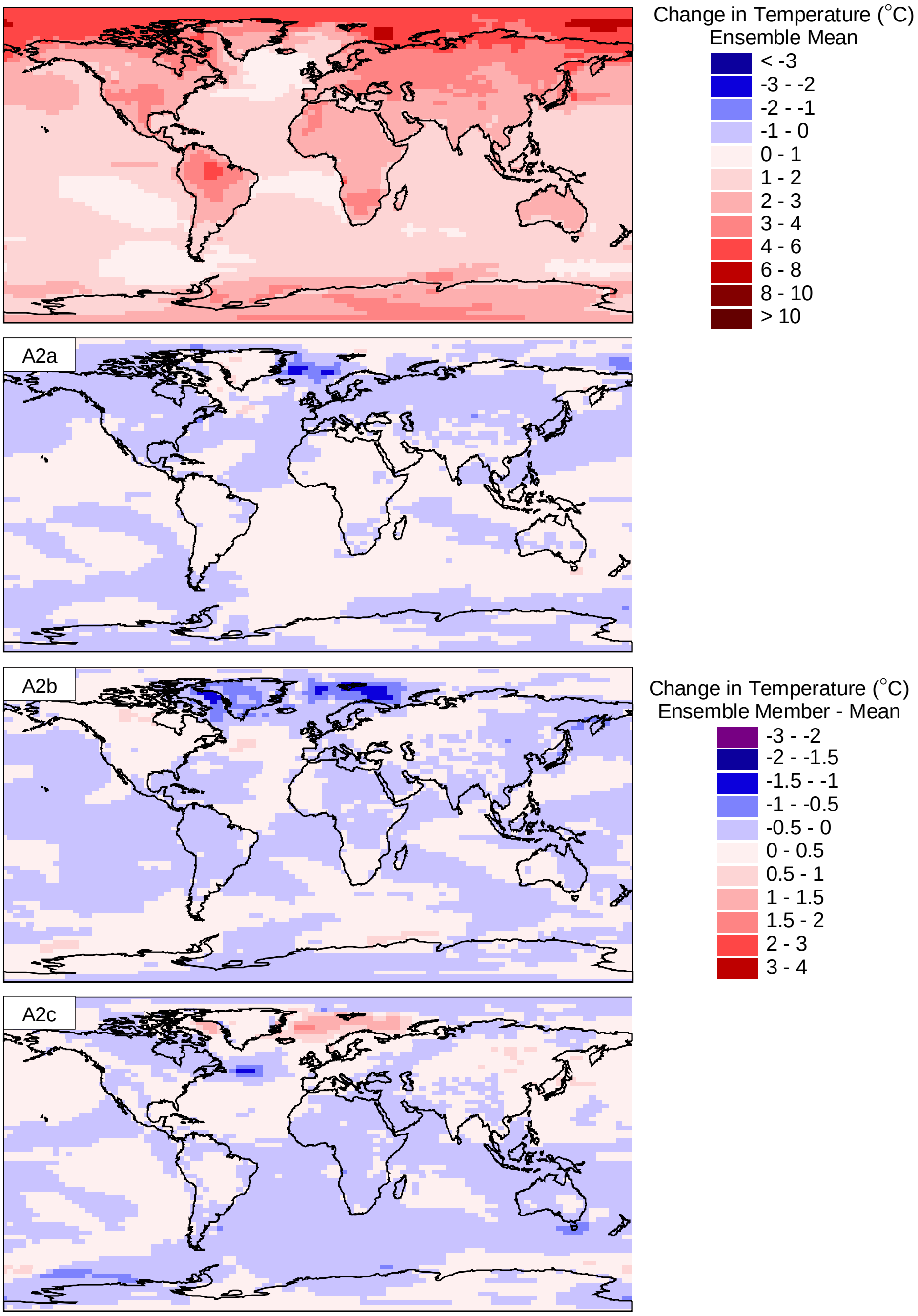
8. Conclusions

8.1. Overview

The future impacts of climate change will depend to a large extent on the future economic, demographic, social and political characteristics of the world. There are several narrative and semi-quantitative scenarios for future global and regional socio-economic development (including the four future worlds used in the GEO-3 assessment: UNEP, 2002; Kemp-Benedict et al., 2002), but the IPCC's SRES narrative storylines and associated socio-economic characterisations were specifically designed to be used in the assessment of future climate change (IPCC, 2000). However, whilst the quantitative characterisations as presented in the SRES report are suitable for estimating future emissions of greenhouse gases, they are at too coarse a spatial resolution for impacts and adaptation assessments.

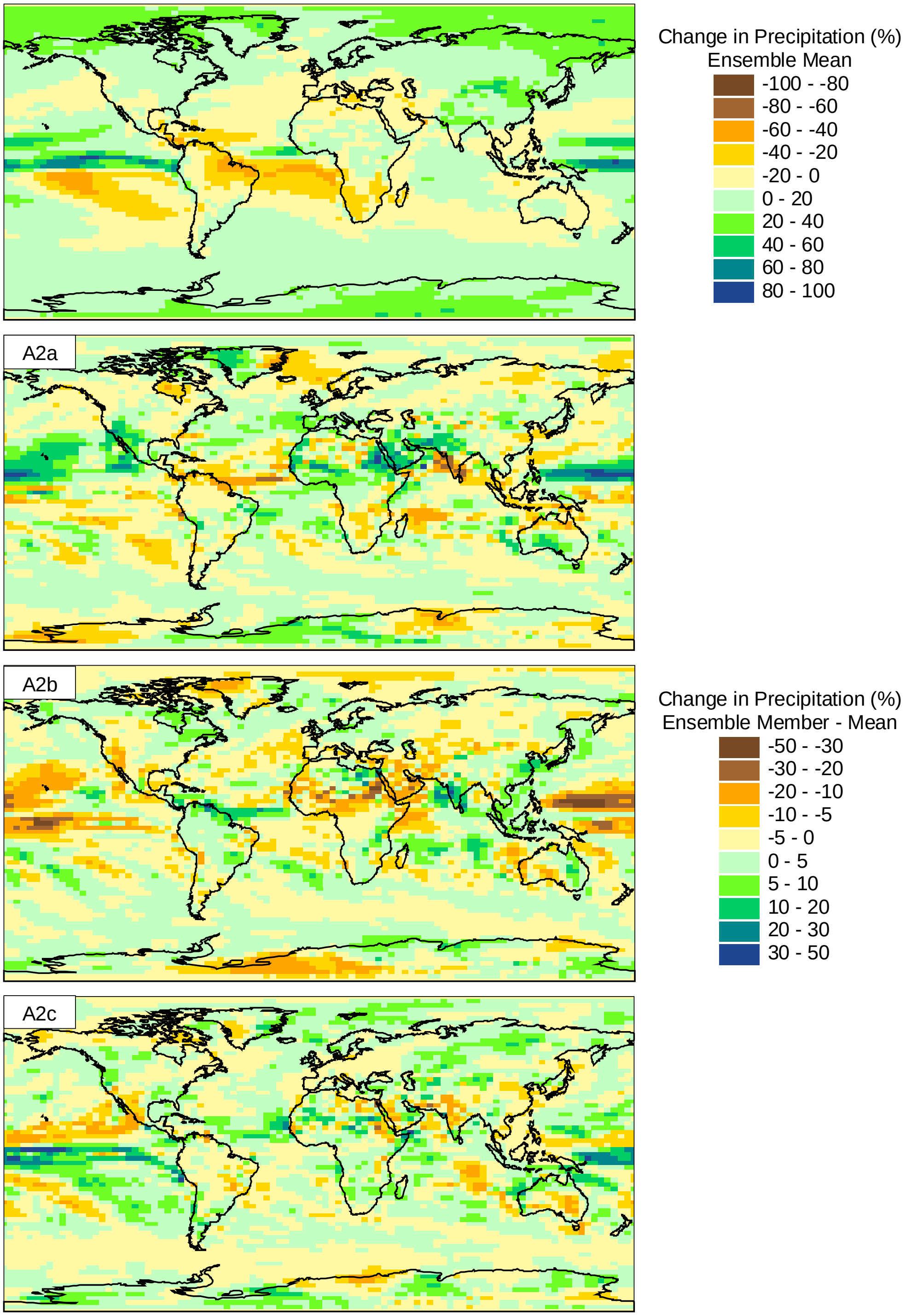
This paper has described how the SRES world-region population and economic data were downscaled to the national and sub-national scales for a global-scale climate impact assessment of future food scarcity (Livermore et al., 2003), water stress (Arnell, 2003), exposure to malaria (Van Lieshout et al., 2003), coastal flood risk and wetland loss (Nicholls, 2003) and terrestrial ecosystems (Levy et al., 2003). Unlike national or regional-scale assessments, where socio-economic scenarios simply need to be "consistent" with the world-region SRES scenarios, the downscaled scenarios used in impact assessments at the global-scale need to be numerically identical to the coarser-scale characterisations.

Population was downscaled from the world region to the national scale by CIESIN and IIASA (Gaffin et al., 2003), and subsequently downscaled to the 0.5° × 0.5° scale for use in the impacts models. To 2050 national estimates are based on national-level projections, but after 2050 it is assumed that population in every country in a world region changes at the regional rate. This can lead to discontinuities where the national growth rate is very different to the regional rate. The second key assumption is that population in every grid cell within a country changes at the national rate: there is no difference between different parts of a country, or



(a)

Fig. 9. Variations in the regional patterns of (a) temperature and (b) precipitation change fields for the 2050s witnessed in a three-member ensemble SRES A2 experiment. The top map is the ensemble mean while the lower three represent the departure of individual members from the mean.



(b)

Fig. 9 (*continued*).

between rural and urban growth rates.[4] It would be a simple matter to incorporate variable rates in different parts of a country—if sub-national projections were available[5]—but rather more difficult to distinguish between rural and urban growth rates. This would require projections of differential growth rates into the future (which would vary with SRES world). The effect

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[4] Although Nicholls (2003) assumed differential rates of growth in the coastal zone.

[5] They are for some large countries, including the USA and China.

of this second assumption is minimised in some of the Fast Track studies which aggregate the 0.5° × 0.5°C cells to larger units (such as watersheds).

National GDP was downscaled from the SRES world-region projections by CIESIN (Gaffin et al., 2003), converting national currencies to US$ using market exchange rates, and assuming that every country in a region grows at the same rate. In general this seems to give robust scenarios, although the different regional definitions in the marker models do lead to some inconsistencies, such as lower GDP for the Large and Small Pacific Islands in the B1 world. This implies that in the B1 world these regions have a lower adaptive capacity than the storyline would suggest. Future impact scenarios should be developed based on common regions to avoid this effect. Using Purchasing Power Parity to combine national GDP totals would produce little difference after 2050, but before then would result in smaller differences between regions than the use of market exchange rates.

The terrestrial ecosystems assessment used the SRES land cover scenarios to determine future cropland extent. However, two of the SRES projections assume a future decline in crop area and an increase in forest cover, and a third assumes little net deforestation over the 21st century: whilst it is accepted that the SRES projections are long-term scenarios, these projections are very inconsistent with current trends and likely future patterns of land use change.

Information in the narrative storylines was also used to make inferences about the capacities of countries to adapt to climate change, specifically for coastal flood defence and exposure to malaria.

8.2. Comparison with characterisations of the GEO-3 scenarios and other global projections

The four socio-economic scenarios developed by the Global Scenario Group and used in UNEP's GEO-3 (UNEP, 2002) have been quantified at the major world-region level (www.gsg.org; Kemp-Benedict et al., 2002). Table 8 summarises the global population under the four GEO-3/GSG scenarios and four SRES storylines. The A1/B1 global population is similar to the "market first" and "policy first" scenarios, and slightly higher by the 2050s than the "sustainability first" scenario. The A2 global population is most similar to, but slightly higher than, the "security first" scenario, and B2 is different to—but within the range of—all of the GEO-3/GSG scenarios. Table 8 also shows the $\mathrm{GDP_{MER}}$ per capita under both sets of four scenarios. A2 is consistently poorer than any of the GEO-3/GSG scenarios, and by the 2050s A1 is richer.

Fig. 8 also compares the GEO-3 and SRES scenarios. It shows the relationship between population and per capita $\mathrm{GDP_{MER}}$ in 2050 for the world and the four major world regions used in the SRES scenarios. There is no clear matching between the two sets of scenarios (as indeed would be expected from the different narrative descriptions of the scenarios), and the relative positioning of the scenarios varies between regions. For example, in each region A1 has the highest per capita $\mathrm{GDP_{MER}}$ of the SRES scenarios, followed by B1 and B2, with A2 the lowest. In three of the regions the "sustainability first" scenario has the highest per capita $\mathrm{GDP_{MER}}$ of the GEO-3/GSG scenarios, but in the OECD region the "markets first" scenario is the richest. The GEO-3/GSG scenarios also show considerably greater variability between regions than the SRES scenarios: the "markets first" scenario, for example, is considerably more unequal than any of the SRES scenarios, and the "sustainability first" scenario is more equal than any of the SRES scenarios. It is, therefore, not possible to extrapolate numerical results from an impact assessment using one set of scenarios to another set of future worlds: each scenario needs to be assessed individually.

Table 8
Comparison of SRES and GEO-3/GSG world population and per capita GDP projections

	Population (millions)		$\mathrm{GDP_{MER}}$ per capita (1990 US$)	
	2025	2050	2025[a]	2050
GEO-3/GSG scenarios				
Markets first	7824	8909	7885	11,640
Policy first	7688	8514	8377	14,141
Security first	8379	10,674	6886	9340
Sustainability first	7486	7909	9818	17,196
SRES scenarios				
A1	7926	8702	9356	20,889
A2	8714	11,295	5598	7409
B1	7926	8702	8260	16,515
B2	8036	9363	7432	12,000

[a] Interpolated between 2020 and 2030 for the SRES projections.

Since the SRES was developed, Lutz et al. (2001) produced some probabilistic projections of future world and regional populations, which make different assumptions about future fertility, mortality and migration rates. All the SRES projections are within Lutz et al.'s (2001) 80% confidence limits by the 2020s, as are the A1/B1 and B2 projections for the 2050s and 2080s. However, the A2 population projection is above the 80% range by the 2050s. Thus, the A2 population scenarios used in this analysis are therefore at the high end of the likely range of possible future population totals.

8.3. Limitations of the SRES scenarios for impact assessment

The attempt to use the SRES scenarios for global-scale impact assessment has identified two key limitations.

First, there are considerable difficulties involved in moving from the scale at which the SRES scenarios were produced (11–13 world regions) to the much finer spatial resolution required by impacts models. A number of rather major assumptions had to be made, most specifically that all parts of a region would change at the same rate: this was applied to population, GDP and land cover.

Second, whilst the SRES land cover trends are consistent with the narrative storylines, they are inconsistent with recent trends. Under none of the storylines is there a sustained continued deforestation, for example, and crop areas decrease under all of them.

A further limitation—noted in the SRES report (IPCC, 2000) but often missed by those interpreting results of assessments—is that the SRES storylines do not cover all possible future worlds. There is no SRES world in which absolute incomes are constant or even fall, for example. An impact assessment based on the SRES storylines therefore would not necessarily span the full range of possible future climate change impacts.

8.4. Uncertainties

Like projections of future climate, projections of future socio-economic conditions under a given storyline are uncertain (Carter et al., 2001). Population projections for a storyline, for example, depend on assumed fertility and mortality rates and, like climate projections, become increasingly uncertain further into the future. Downscaling from world region to country, and to regions within a country, adds even more uncertainty. Projected future GDP for a storyline is even more uncertain, because it depends on (i) specific economic assumptions made about growth and the implementation of technological changes, (ii) the characteristics of the economic model used to project GDP, and (iii) assumptions about future exchange rates. Again, downscaling adds further uncertainty. The different integrated assessment models used to forecast GDP for the SRES storylines produce a range in global GDP, for a given storyline, of up to 30% (from IPCC, 2000, Table SPM-1a). Similarly, the different models produce very different estimates of future land cover.

8.5. Next steps: enhanced impact assessment with the SRES storylines

The limitations and uncertainties summarised above suggest a number of ways of refining global and regional-scale impacts assessments: different issues may be associated with constructing socio-economic scenarios for site-specific assessments.

First, more sophisticated procedures should be used to downscale the SRES characterisations from regional to national or finer scales. This would involve two components: creating "downscaled narrative scenarios" which describe how different parts of a region change in relation to the regional sum, and the development of technical procedures to apply, for example, differential population growth rates in different parts of a country. It would, however, probably be necessary to relax (by how much?) the constraint that the downscaled data agree with the SRES regional totals when re-aggregated. Stochastic models of the evolution of the spatial pattern of growth—as applied for example by Rey (2003)—could be explored.

Second, it is important to consider uncertainties in the population, GDP and land cover (and indeed other variables) for a given storyline (Carter et al., 2001). It has become standard practice to use several climate models to characterise uncertainty in future climate: it should also become standard practice to use different feasible socio-economic characteristics, based on different models or qualitative projections, for each storyline. One way to estimate uncertainty bounds for a given storyline would be to run an ensemble of population and GDP projections, reflecting different assumptions about model parameters, and repeat the impact assessment for each socio-economic ensemble member (using, for example, the large number of population projections made by Lutz et al., 2001). Alternatively, it would be possible to repeat the impact assessments with "high" and "low" population and GDP projections.

Third, if the aim of the impact assessment is to explore the range of possible future impacts of climate change—rather than just the impacts under the SRES futures—then it will be necessary to use additional scenarios of socio-economic futures, such as those produced for GEO-3. One of the general conclusions from the Fast Track studies (Arnell, 2003; Levy et al., 2003; Nicholls, 2003; Livermore et al., 2003; van Lieshout et al., 2003) is that over the next 50 years at least there is relatively little difference in climate change between the different SRES emissions scenarios. It is therefore a reasonable first approximation to apply these climate changes with other future socio-economic worlds in order to characterise the full range of possible future impacts of climate change.

Acknowledgements

The downscaling of the population and GDP scenarios to the national scale was undertaken by Stuart Gaffin (CIESIN) and Wolfgang Lutz (IIASA), and the data are available on the IPCC's Data Distribution Centre Socioeconomic Data website (sres.ciesin.columbia.edu/tgcia). The downscaling to finer resolutions and derivation of other quantitative indicators was undertaken by the Fast Track project group, with funding from the UK Department for the Environment, Food and Rural Affairs (Defra) under contracts EPG1/1/137, EPG1/1/70, EPG1/1/food, EPG1/1/140, and EPG1/1/39. The HadCM3 climate change scenarios were provided through the Climate Impacts LINK project, funded by Defra (contract EPG1/1/68).

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