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Project title: ENSEMBLE-based Predictions of Climate Changes and their Impacts

Instrument: Integrated Project

Thematic Priority: Global Change and Ecosystems

D7.1c A review of the baseline scenarios that have emerged since the SRES, and the selection of one scenario, based on that which gives the most new scientific information over and above the SRES scenarios, to be made available for the ENSEMBLES Stream 2 simulations

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A NEW SCENARIO FOR GLOBAL CARBON DIOXIDE EMISSIONS IN THE 21^ST^ CENTURY

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1. Introduction

The emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC) are commonly used for research into climate change, estimates of the impacts of climate change, and analysis of greenhouse gas emission reduction policies. The SRES scenarios (Nakicenovic and Swart, 2000), the latest set of IPCC scenarios, were also used as the basis of the scenarios of the Millennium Ecosystem Assessment (2005) and national scenarios, e.g., in Britain (UKCIP, 2001). The SRES scenarios have been severely criticised (Castles and Henderson, 2003a,b; Castles, 2004; Henderson, 2005), while the improper handling of justified critique (IPCC, 2003; Nakicenovic et al., 2003; Grübler et al., 2004) has cast doubt on the credibility of the entire IPCC (Economist, 2003a,b, 2004; Michaels, 2003; House of Lords, 2005).

The initial critique of the SRES scenarios focussed on economic accounting (Nordhaus, forthcoming). However, the use of market exchange rates rather than the more appropriate purchasing power exchange rates becomes particularly critical if income convergence is assumed (Dixon and Rimmer, 2006), a contestable assumption (Tol, 2006). The bias thus introduced is partially offset by the assumption of convergence of energy intensities (Manne *et al.*, 2005), an assumption with some empirical support (Miketa and Mulder, 2005).

The rapid convergence of per capita income is a known characteristic of the modern growth theory developed by Solow (1956, 1987) and Koopmans (1967). Although new growth theory superseded modern growth theory since the work of Romer (1986, 1987, 1990), integrated assessment models have not been updated. New growth theory is distinct from modern growth theory in that technological change is *endogenous*, rather than *exogenous*. As a corollary, convergence of per capita income does not follow, and is indeed not observed (Barro and Sala-i-Martin, 1995).

The fact that a crucial component of the SRES emission scenarios is at odds with the observations is probably because the models used to generate these scenarios have never been validated (see O'Neill and Van Vuuren, forthcoming, for a first attempt). Indeed, the models were calibrated to a recent year and run forward for a century or more. Interestingly, the SRES scenarios typically show a trend break where the data end and the scenario begins.

Criticising the SRES scenarios is easy. This paper is an attempt to offer an alternative, that is better in at least some respects. The model presented here is in line with recent insights into growth and development, and the model is calibrated to observations for the last 150 years. The work of economic historians, led by Angus Maddison (2001), enables this. A follow-up to Tol (forthcoming), this paper adjusts the US scenario presented there and extends it to the rest of the world. As such, I here address my main criticism of the SRES scenarios, namely income convergence. Naturally, the model is calibrated in purchasing-power dollars. Note that the representation of energy is considerably simpler here than in Tol (forthcoming).

The paper is structured as follows. Section 2 describes the model. Section 3 presents the base scenario. Section 4 concludes.

2. The model

2.1. Population

The population model used is CHIMP 1.0, described in Fisher *et al.* (2006). Like most demographic models, CHIMP has population cohorts. Every period, the larger part of a cohort is promoted to the next cohort, while the remainder dies. The size of the youngest cohort is proportional to the size of the cohorts of women of child-bearing age. Furthermore, people can migrate between the 16 regions of the model. Unlike most demographic models, fertility, mortality, and migration are partly driven by per capita income. This is particularly pronounced for the poorer regions. For the richer regions, exogenous trends in mortality and fertility are more important. Migration, however, is driven by the income gap between the regions.

2.2. Economic growth

The economic model is David Romer's (1996) macro-version of Paul Romer's (1990) micro-based model of economic growth, except for the savings' rate. Production is driven by labour, capital and knowledge:

(1) $$Y(t) = H(t)\left((1-\gamma_K)K(t)\right)^{\lambda}\left((1-\gamma_L)L(t)\right)^{1-\lambda}$$

where Y is production, H is technology, K is capital and L is labour (not population); t denotes times; and γ and λ are parameters.

Capital accumulates as

(2) $$K(t+1) = (1-\delta_K)K(t) + s(t)Y(t)$$

where s is the savings' rate and δ is depreciation.

Knowledge accumulates as

$$(3) \qquad H(t+1) = (1-\delta_A)H(t) + \beta\left(\gamma_K K(t)\right)^{\kappa}\left(\gamma_L L(t)\right)^{\kappa} H(t)^{\kappa}$$

where κ, β, and δ are parameters.

The savings' rate follows

$$(4) \qquad s(t) = \vartheta + \psi\frac{L(t)}{P(t)}$$

where P denotes the population and φ and ψ are parameters.[1]

Equations (1)-(4) have 9 parameters in total, whose values and sources are given in Table 1. Most parameters are set to values that are typical in the literature. The base rate of depreciation equals the difference between the observed gross and net savings in recent decades; the depreciation rate is used to calibrate the model to such things as wars and economic crises. The shares of capital and labour in R&D in 2000 are from observations; in other years, the values are such that the marginal returns on capital and labour are equal in the production of knowledge and the production of the consumption good. The parameters of Equation (4) are based on a linear regression. The initial value of the capital stock K is set to its steady state value. The initial value of the knowledge stock H is set such that the predicted GDP matches the observed one for 1850. The capital share of knowledge production κ is set by calibration; the distance between the observed and modelled GDP in 2002 is minimised.

2.3. Energy use and emissions

Energy use follows the EMF14 ground rules as also used in MERGE: The autonomous energy efficiency improvement equals one half of the growth rate of per capita income.

The rate of decarbonisation of energy supply follows the A2 scenario (in its IMAGE incarnation), the SRES scenario that is most in line with historical developments.

Sulphur emissions follow the FUND specification, which in turn is modelled on IMAGE. Sulphur emissions increase with population (elasticity: 0.33), decrease with income (elasticity: 0.45), and decrease with energy efficiency and decarbonisation (elasticity: 1.02).

3. Results

3.1. Population

Figure 1 shows the population projections. The world population reaches a maximum of about 11 million people around 2150, and gradually declines after that. Figure 2 shows that the E1 scenario most resembles the SRES A1 and B1 scenarios, at least when these

[1] Earlier versions of the model had a constant savings' rate, but then the technology parameter β in equation (3) has to vary with time. Calibration did not reveal a regular, interpretable pattern for β.

scenarios are run with the same model (CHIMP). Compared to the original scenarios, E1 is somewhere between B2 and IS92a (cf. Table 2). Note that CHIMP projects much higher populations in Africa and much less people in China than does the IPCC.

3.2. Economic growth

Figure 3 shows the projected per capita income. Per capita income is projected to be lower in the USA than in Tol (forthcoming). This is largely due to the fact that in the current version of the model, capital and labour shift out of R&D as it finds more gainful employment elsewhere. For the US, the E1 scenario is somewhat on the low side of the SRES range. The same is true for Australia and New Zealand and for Western Europe. Canada is in the middle. Per capita income in Japan and South Korea is projected to be higher than in the SRES scenarios. In the Romer-Romer model, R&D is the fundamental driver of growth. The calibrated model assumes that the recent slack in Japanese growth is due to a dysfunctional capital market and puts Japan back on its knowledge-driven high-growth path in the near future.

For the non-OECD regions, differences between market exchange rates and purchasing power exchange rates are substantial. As the data use purchasing power exchange rates, the SRES scenarios were converted using an income elasticity of 0.28, as in Tol (2006).

Eastern Europe and the former Soviet Union do not grow very fast in the E1 scenario. The reasons are demographic decline and an inability to switch to knowledge-driven growth. The same is true for South Asia and the Small Island States and, to a lesser extent, China and South America. The model interprets the recent rapid growth in China and India as driven by capital deepening, which is unsustainable. The other regions grow at a rate that is somewhere in the middle of the SRES range. Remarkably, per capita income in Sub-Saharan Africa will overtake that in China and South Asia.

The E1 scenario shows a mixed pattern of income convergence and divergence, in line with the empirical evidence.

3.3. Energy and emissions

Figure 4 shows the projected emissions of carbon dioxide. Although the underlying demographic and economic scenario is very different, emissions in the E1 scenario are very much like the emissions in the B1 scenario.

Figure 5 shows the projected emissions of sulphur dioxide. Emissions fall everywhere as clean technology spreads from the OECD to the rest of the world and concerns over acidification rise with rising incomes.

4. Conclusion

In the paper, a new baseline emission scenario is presented, dubbed E1. The new scenario is calibrated with purchasing power exchange rates and uses a new growth model as the engine. In this sense, it is superior to the SRES scenarios. On the other hand, the representation of the energy sector is very rudimentary.

The pattern of economic growth in the E1 scenario is very different than that in the SRES scenarios. However, global carbon dioxide emissions are well within the SRES range – and in fact closely track the B1 scenario. This confirms the increasingly heard conjecture that the SRES scenarios are fine for doing climate research, but perhaps less suitable for studying climate policy.

Acknowledgements

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Table 2. Population sizes (millions) for the 16 regions in 2100 for six alternative economic scenarios for our projections (CHIMP) and the IPCC projections (IS92a and SRES).

	E1	IS92a		A1		A2		B1		B2	
	CHIMP	CHIMP	IS92a	CHIMP	SRES	CHIMP	SRES	CHIMP	SRES	CHIMP	SRES
USA	442	460	291	448	333	447	450	445	334	440	278
CAN	55	55	33	53	38	54	52	53	38	52	32
WEU	749	773	394	715	458	751	619	713	459	713	383
JPK	262	266	227	265	207	256	279	259	207	254	172
ANZ	32	33	31	32	28	32	38	32	28	32	23
EEU	72	77	121	74	94	75	200	77	93	78	110
FSU	266	265	291	276	226	264	481	279	224	285	264
MDE	600	613	544	571	202	610	521	574	197	571	364
CAM	295	318	217	297	215	321	432	310	206	319	341
SAM	584	600	541	588	536	592	1080	589	514	599	852
SAS	2676	2390	2623	1724	1135	2294	2922	1902	1102	1937	2039
SEA	968	1018	1062	920	459	1014	1183	932	446	949	826
CHI	967	1177	1687	1303	1035	1119	2664	1265	1005	1232	1859
NAF	254	267	408	225	228	267	459	237	219	259	362
SSA	2628	3441	1903	2633	1064	3630	2143	2849	1020	3255	1691
SIS	201	192	67	172	66	190	133	179	63	188	105
World	11051	11947	10438	10298	6323	11915	13655	10695	6155	11163	9701

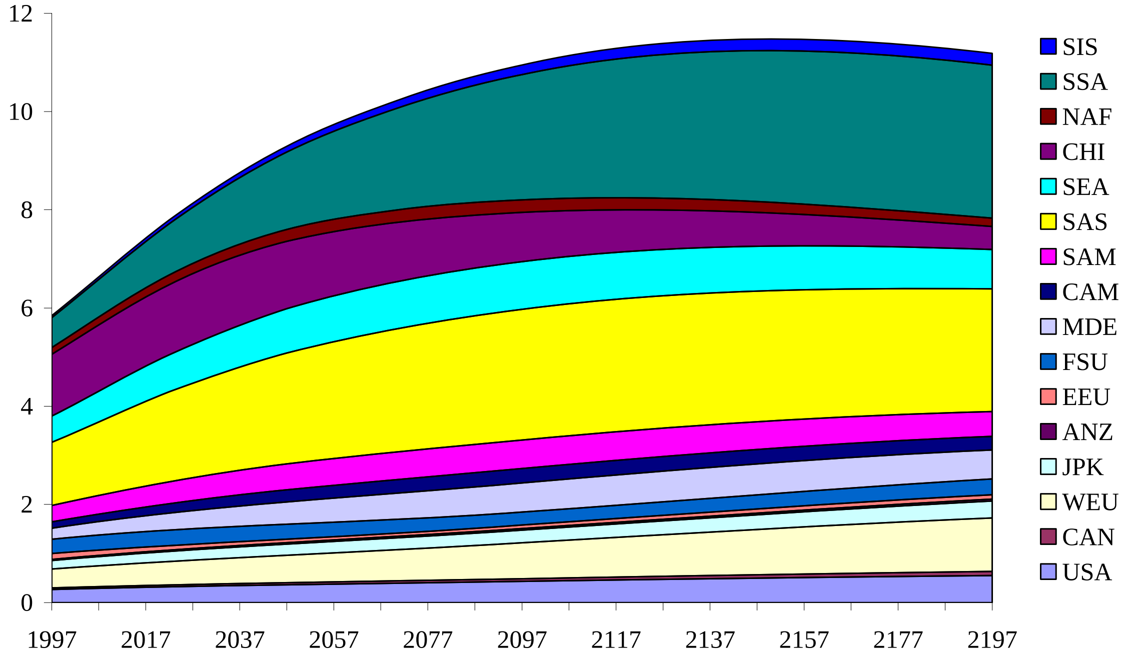


Figure 1. Regional population in the E1 scenario.

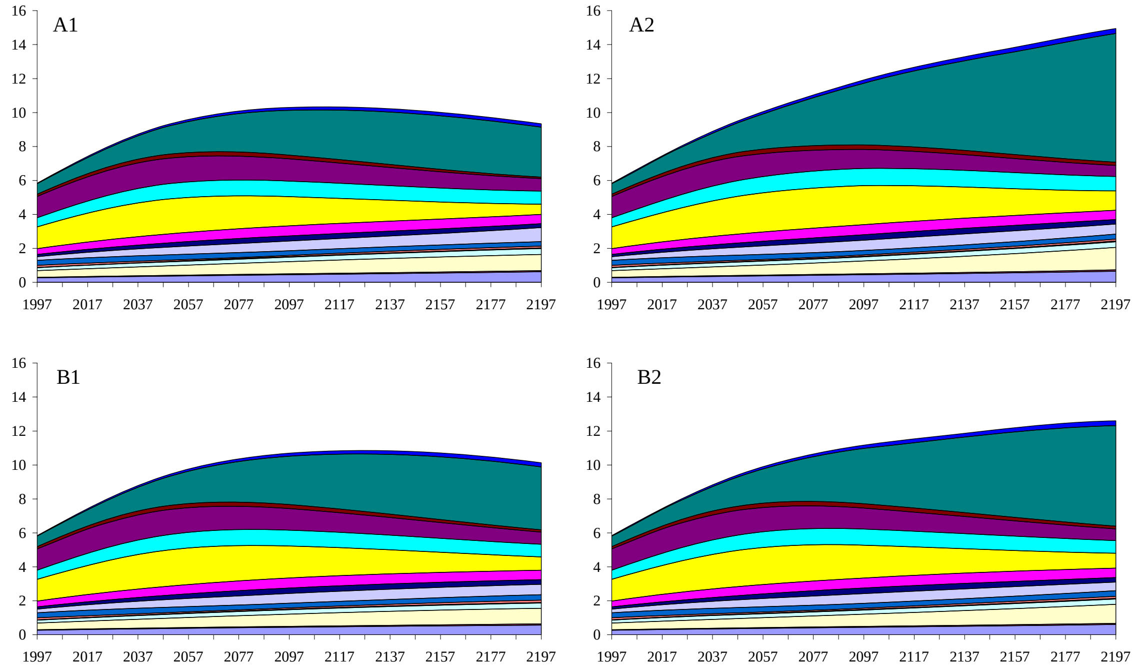
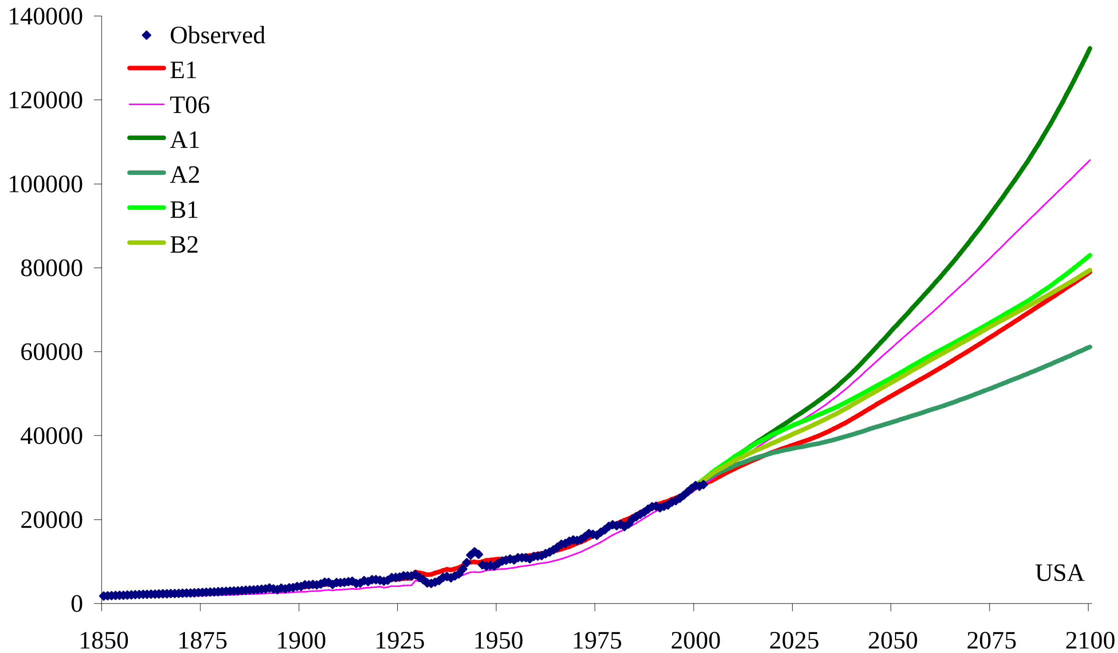


Figure 2. Projected population sizes for 16 world regions for the period 1997-2197 for the four SRES scenarios of per capita income. Source: Fisher *et al.* (2006).



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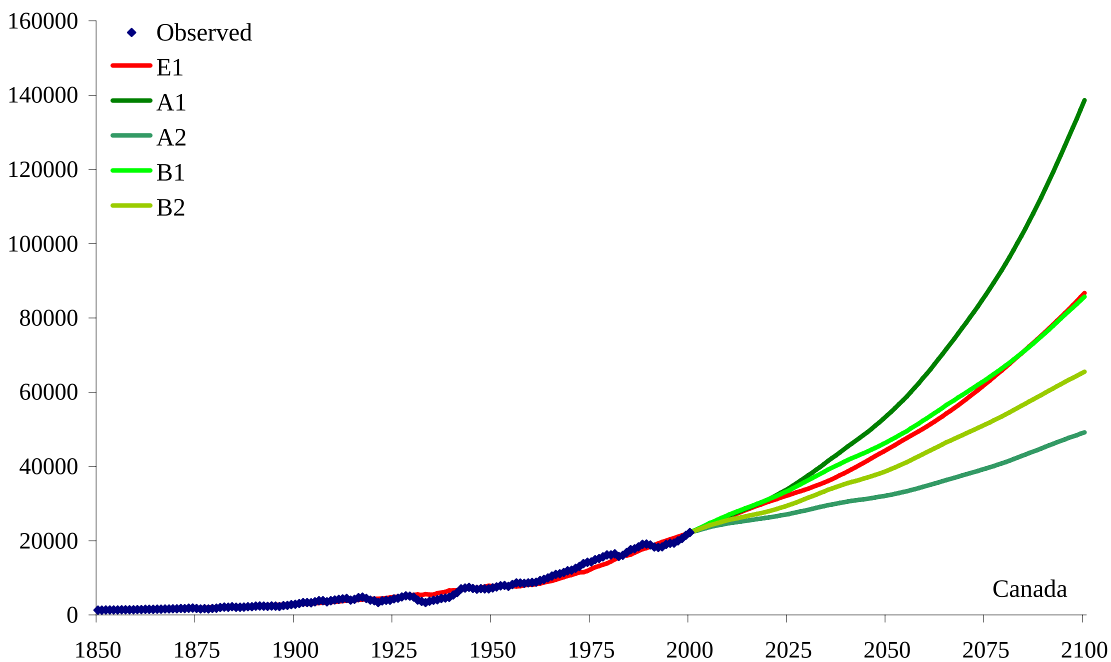

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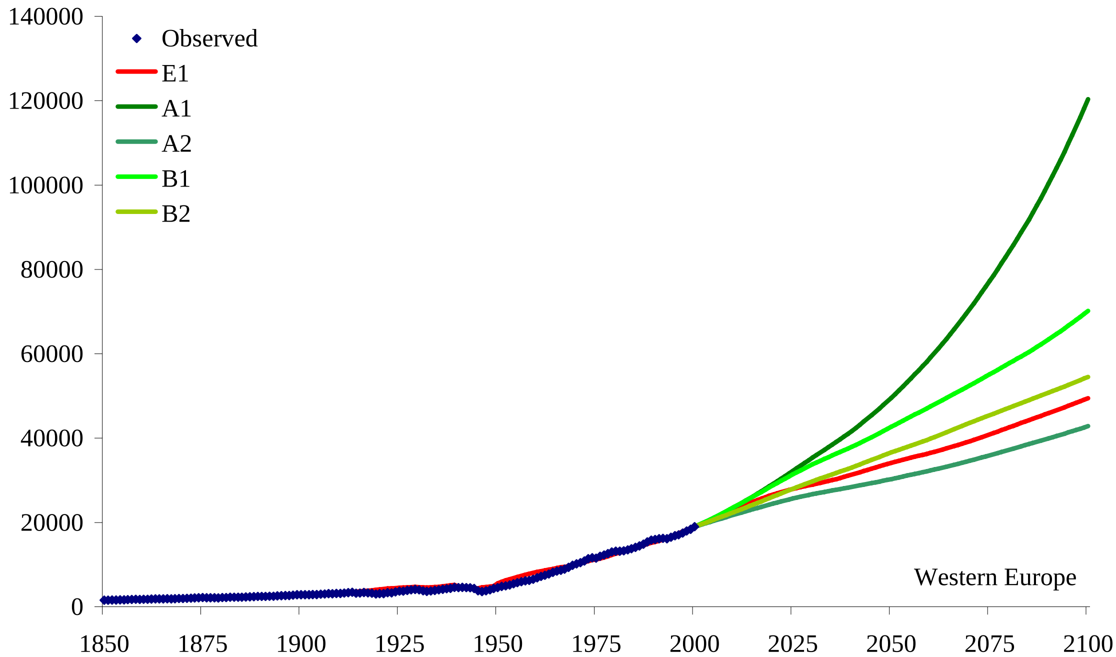
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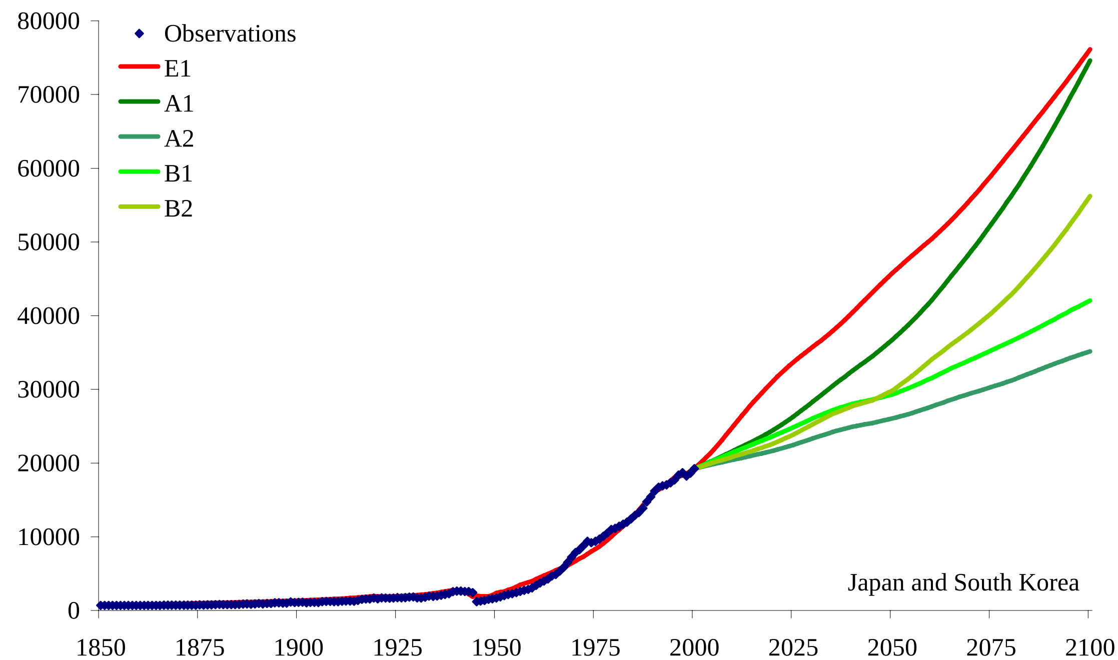
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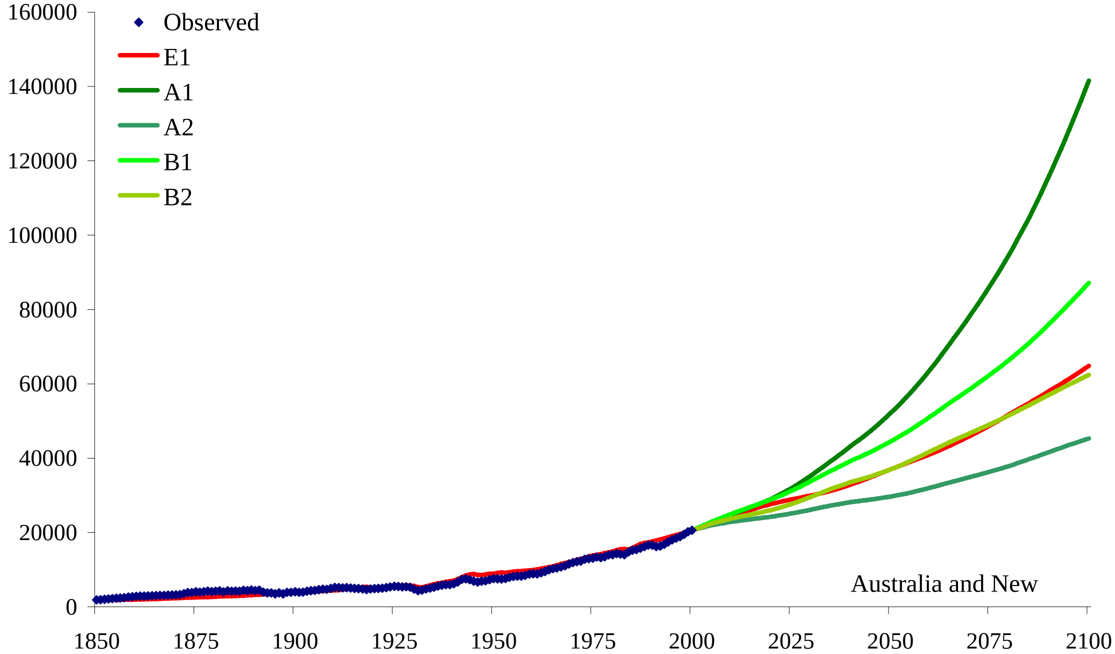

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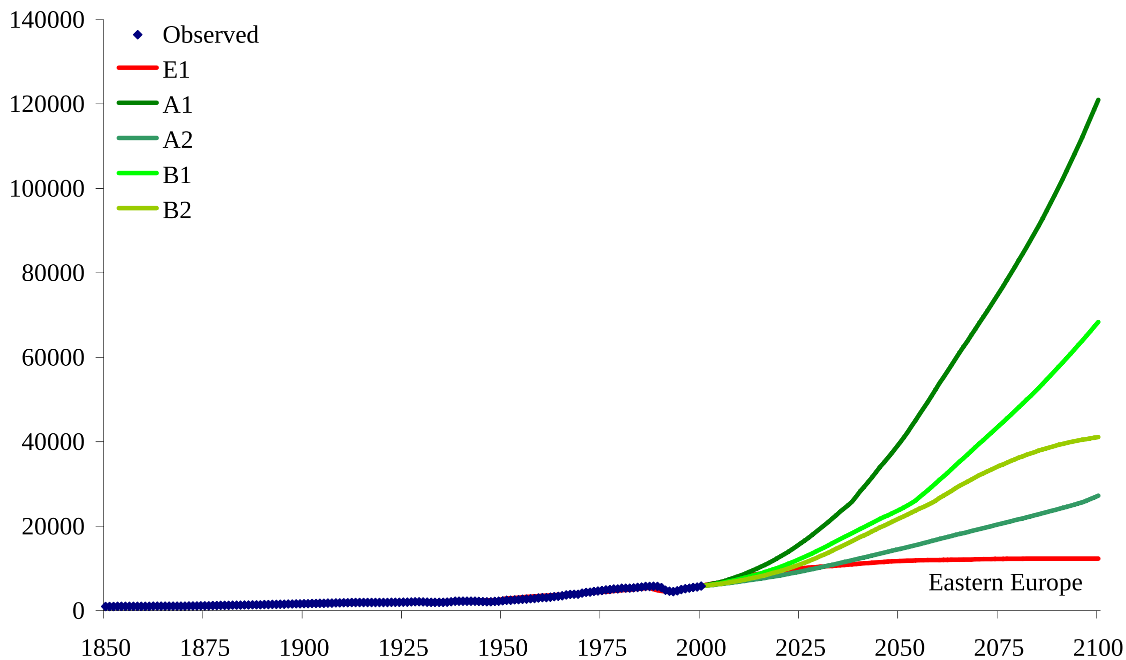

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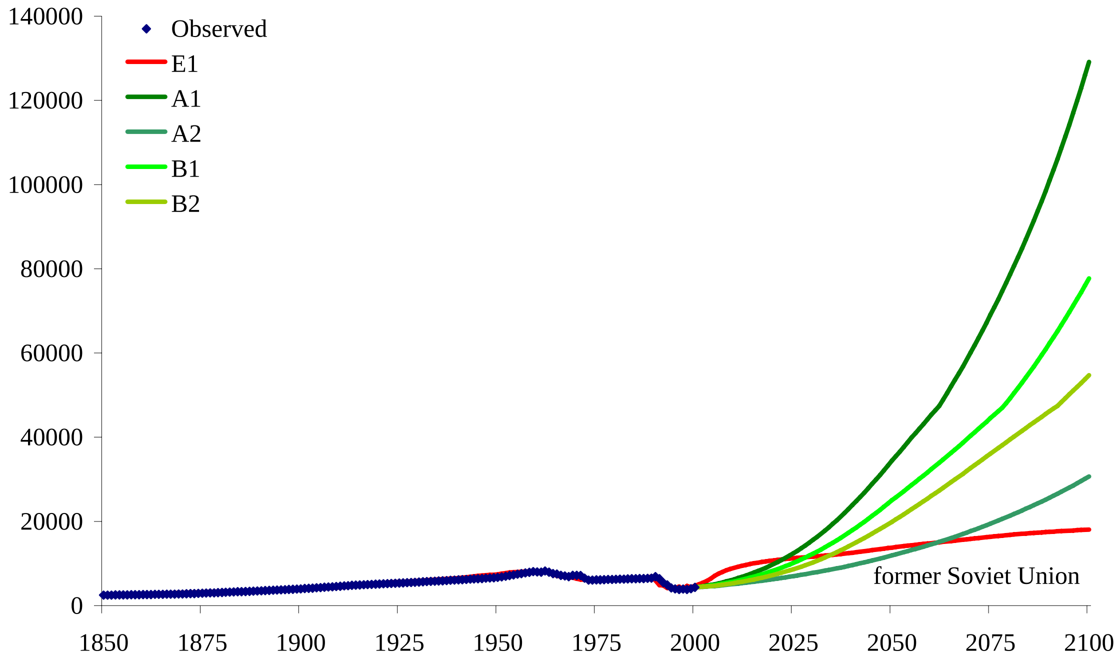
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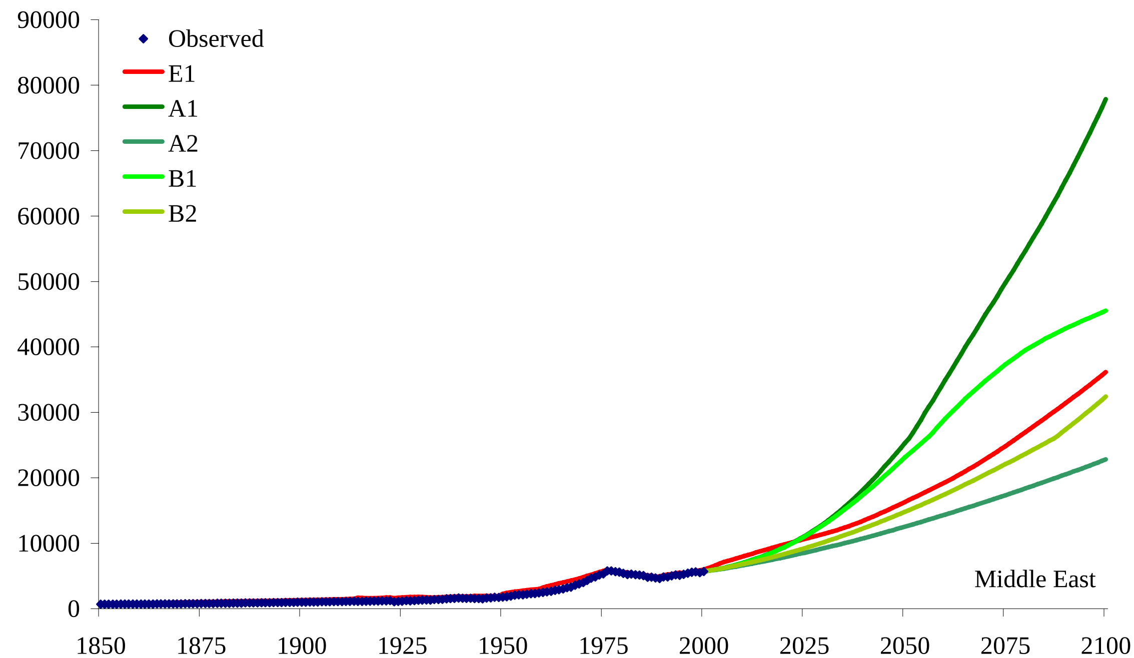
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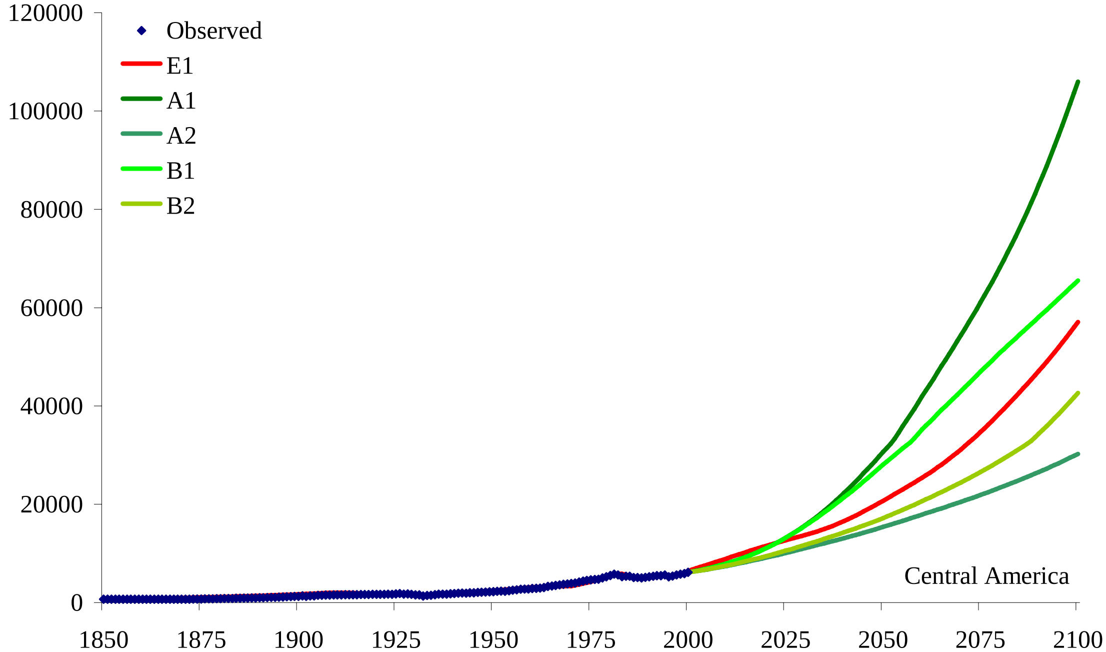
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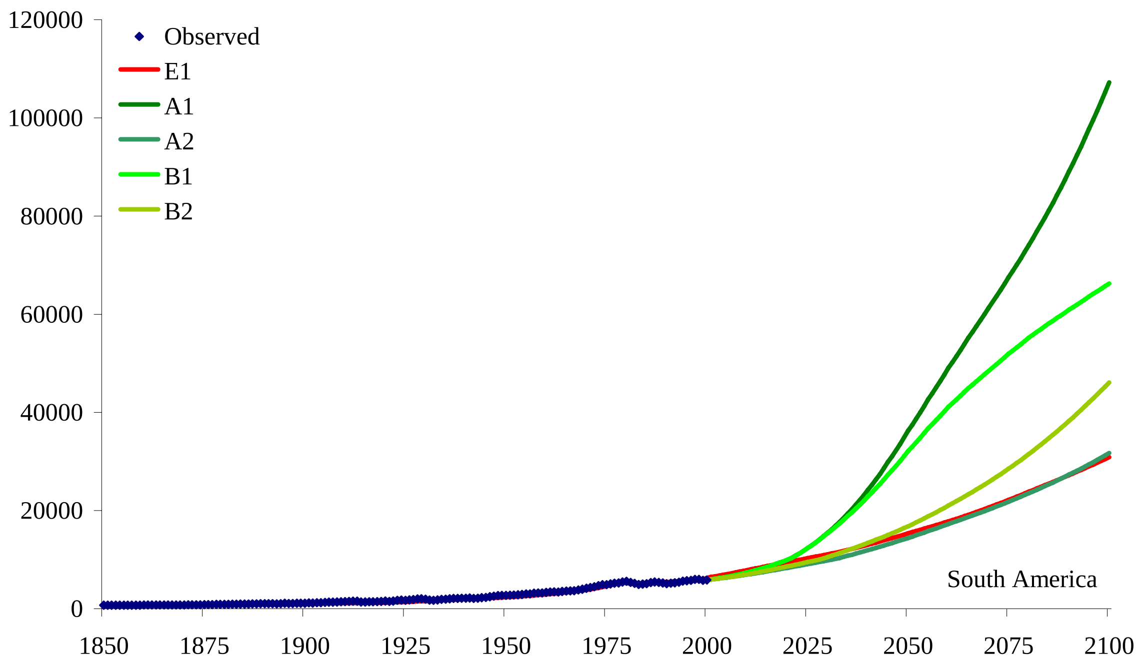
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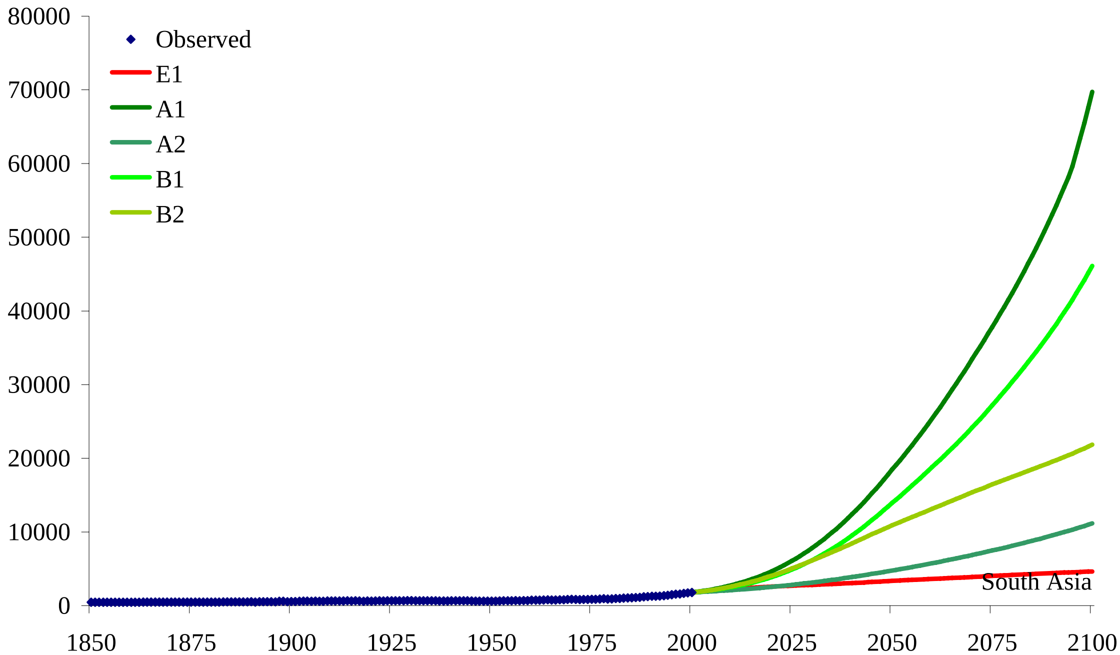
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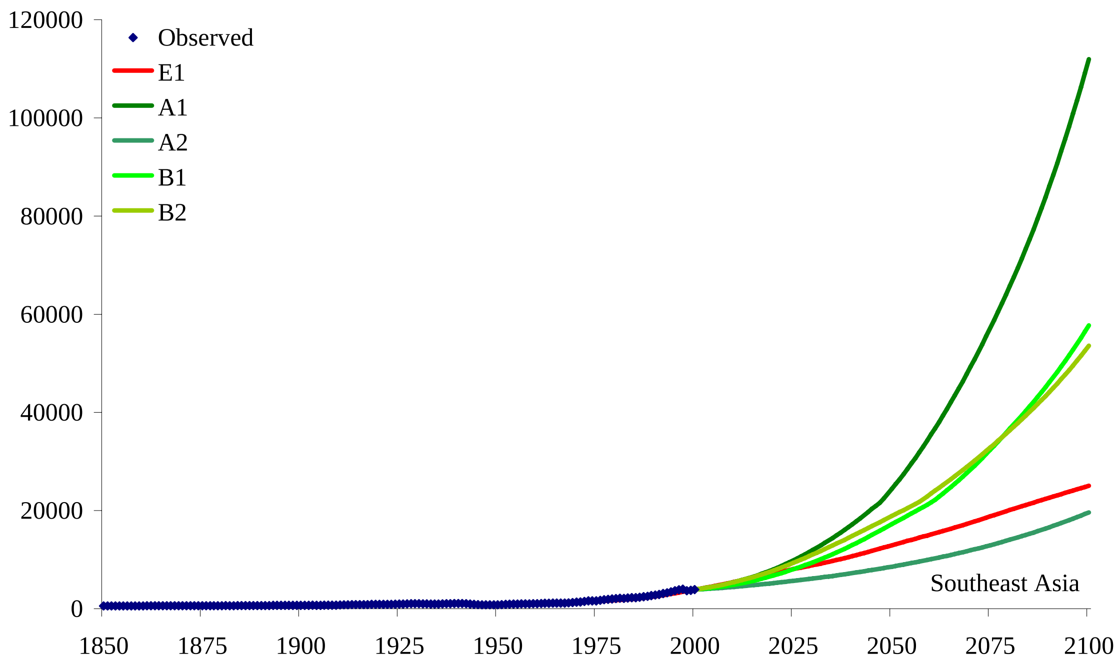
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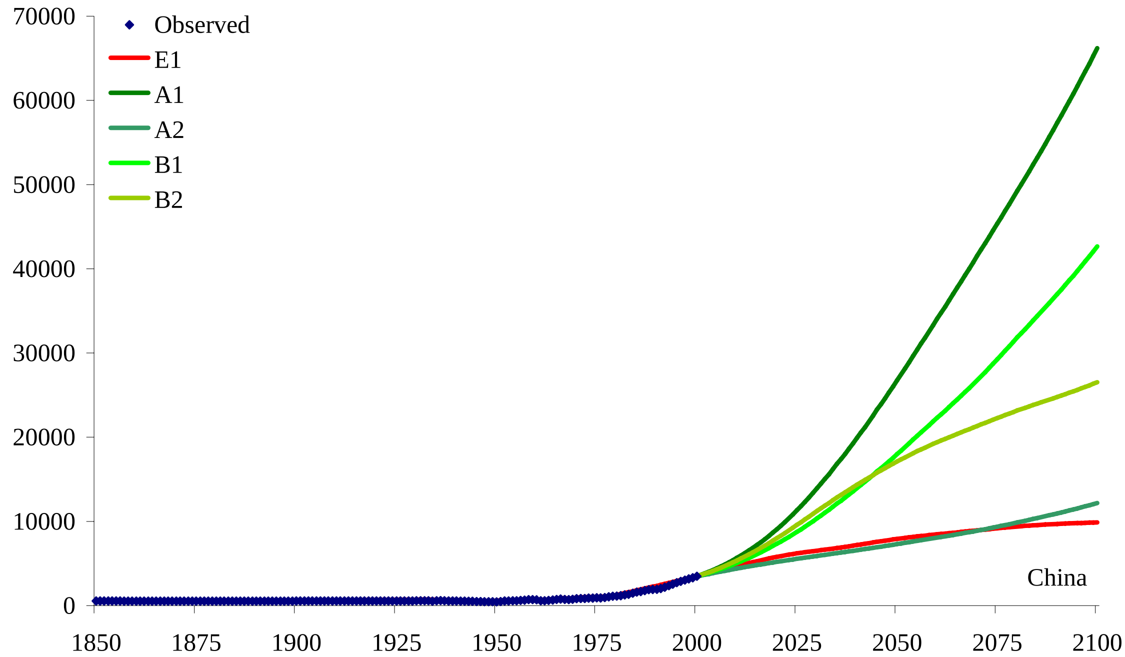

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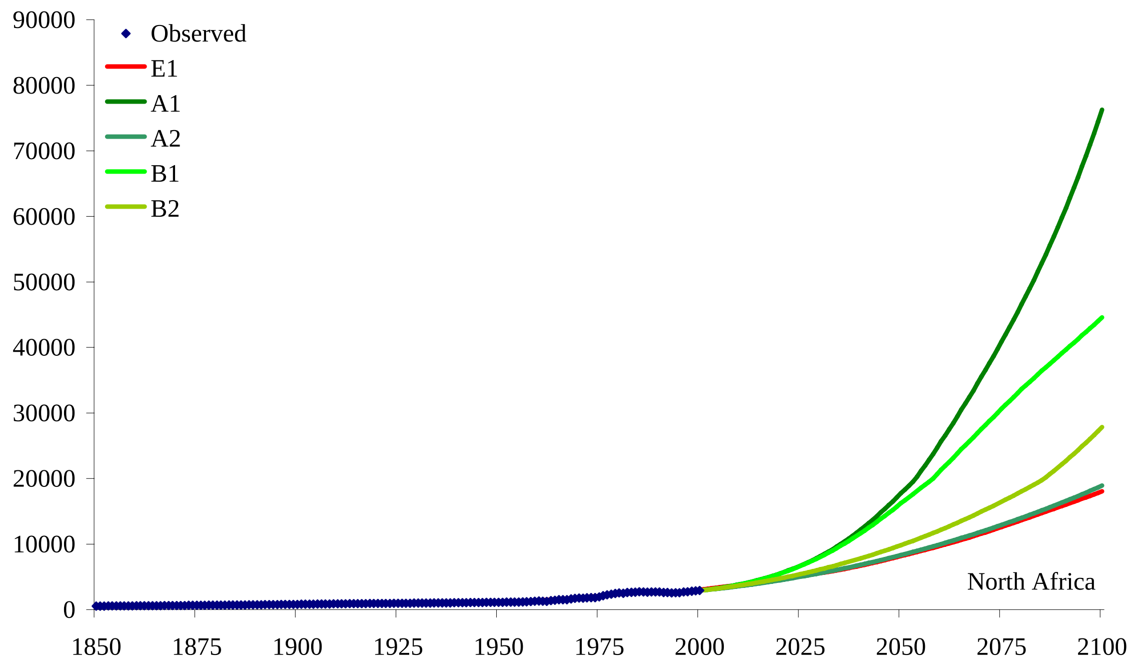
50000
40000
30000
20000
10000
0
1850
1875
1900
1925
1950
1975
2000
2025
2050
2075
2100



Observed
E1
A1
A2
B1
B2
North Africa
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
1850
1875
1900
1925
1950
1975
2000
2025
2050
2075
2100

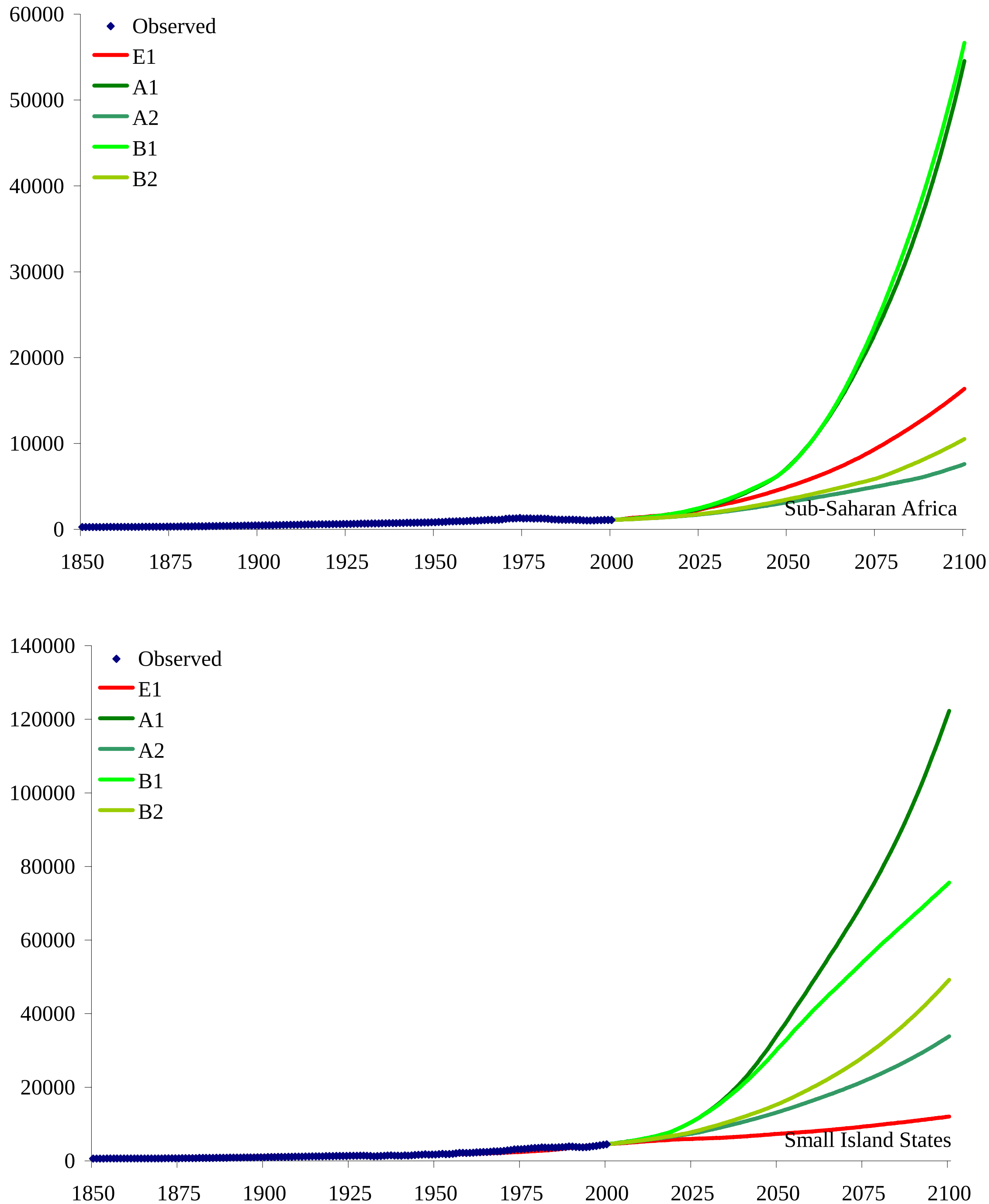


Figure 3. Regional per capita income (in 1990 Geary-Khamis dollars) as observed and as projected by the A1, A2, B1, B2, and E1 scenarios.

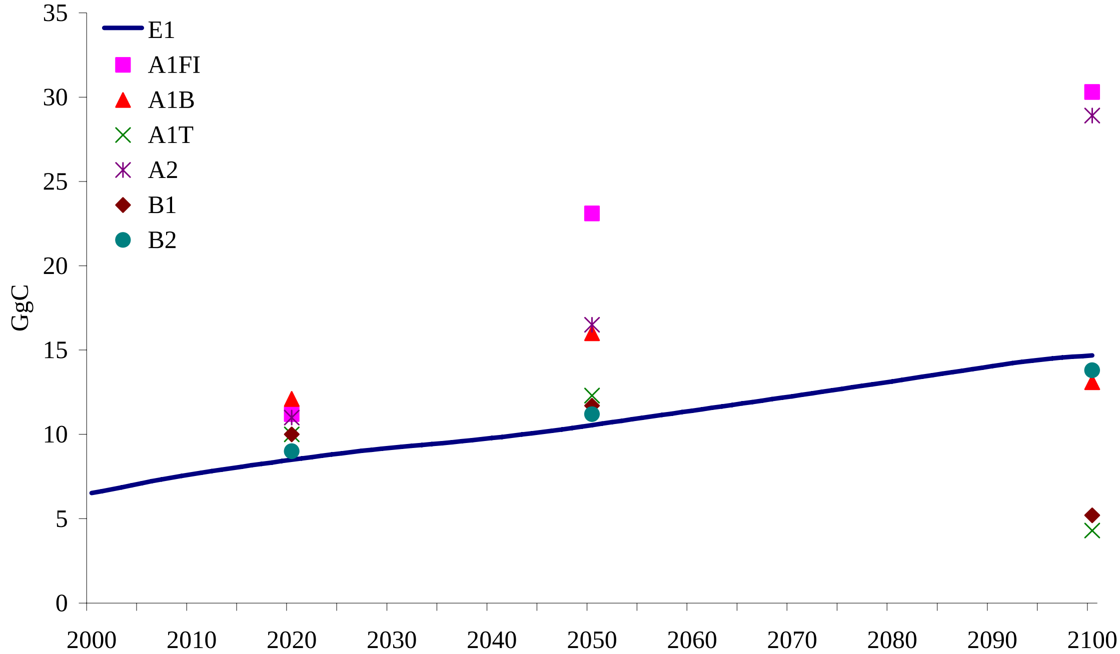


Figure 4. Global carbon dioxide emissions according to the E1 scenario and the six SRES marker scenarios.

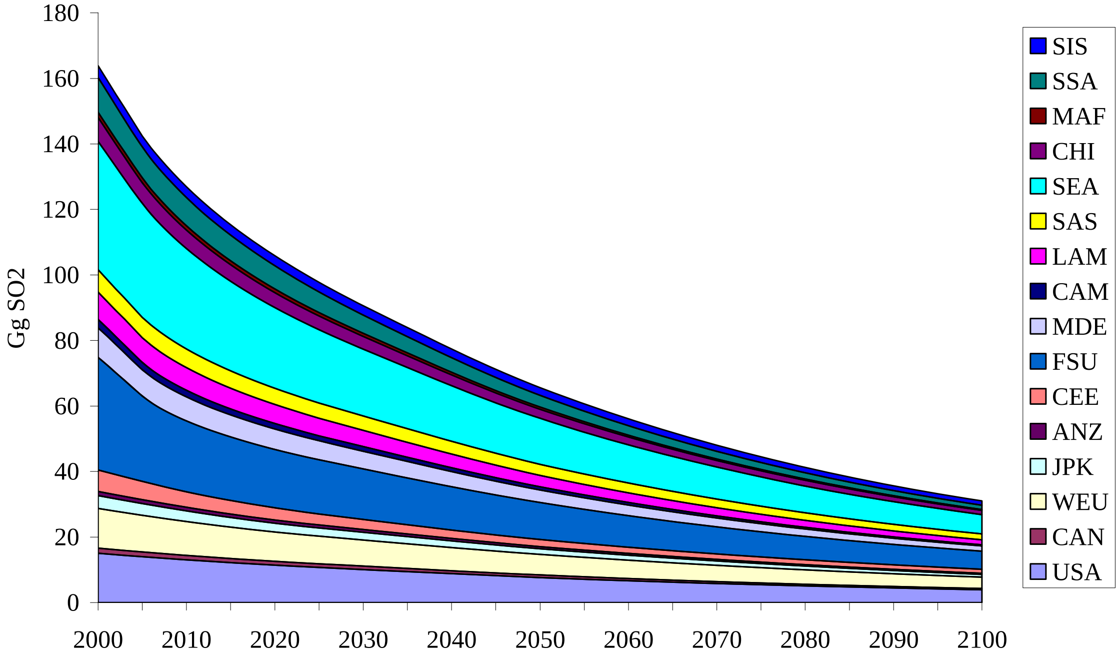


Figure 5. Regional sulphur dioxide emissions.

Table 1. Parameters of the model.

Symbol	Description	Value		Source
Growth				
γ_K	Share of capital in production	.0263	(.0026)	WRI
γ_L	Share of labour in production	.0074	(.0007)	WRI
λ	Capital share in production	.20	(.002)	This paper
κ	Capital share in knowledge production	.29	(.003)	Calibration
φ	Constant savings' rate	31.2	(6.1)	Regression
ψ	Shift factor in savings' rate	-28.4	(5.6)	Regression
δ_K	Depreciation of capital	.100	(.010)	This paper
δ_H	Depreciation of knowledge	.020	(.002)	This paper
Structure				
$\bar{A}$	Subsistence agriculture	485	(49)	Least squares
$\underline{S}$	Household services	1003	(100)	Least squares
$(1-\alpha)(g_M-g_A)$	Technological bias agriculture	Fig A1		Least squares
$(1-\sigma)(g_M-g_S)$	Technological bias services	Fig A1		Least squares
Energy				
	Annual energy intensity decline, agriculture, percent	0.79	(0.41)	This paper
	Annual energy intensity decline, manufacturing, percent	0.84	(0.63)	This paper
	Annual energy intensity decline, services, percent	1.10	(0.52)	This paper
	Annual energy intensity decline, transport, percent	0.79	(0.31)	This paper
	Annual energy intensity decline, residential, percent	0.54	(0.20)	This paper
	Conversion efficiency decline, percent	0.33	($0.17\ 10^{-4}$)	Regression
	Annual relative price change, coal, percent	-0.45	(1.15)	This paper
	Annual relative price change, oil, percent	-2.01	(1.69)	This paper
	Annual relative price change, gas, percent	-1.36	(2.70)	This paper
	Annual relative price change, nuclear, percent	-1.38	(4.96)	This paper
	Annual relative price change, hydro, percent	-1.79	(4.80)	This paper

	Annual relative price change, other, percent	0.22	(2.35)	This paper