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2011 Environ. Res. Lett. 6 034005

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The response of the climate system to very high greenhouse gas emission scenarios

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Received 18 April 2011

Accepted for publication 17 June 2011

Published 5 July 2011

Online at stacks.iop.org/ERL/6/034005

Abstract

Well informed decisions on climate policy necessitate simulation of the climate system for a sufficiently wide range of emissions scenarios. While recent literature has been devoted to low emissions futures, the potential for very high emissions has not been thoroughly explored. We specify two illustrative emissions scenarios that are significantly higher than the A1FI scenario, the highest scenario considered in past IPCC reports, and simulate them in a global climate model to investigate their climate change implications. Relative to the A1FI scenario, our highest scenario results in an additional 2 K of global mean warming above A1FI levels by 2100, a complete loss of arctic summer sea-ice by 2070 and an additional 43% sea level rise due to thermal expansion above A1FI levels by 2100. Regional maximum temperature increases from late 20th century values are 50–100% greater than A1FI increases, with some regions such as the Central US, the Tibetan plateau and Alaska showing a 300–400% increase above A1FI levels.

Keywords: climate, emissions scenarios, impacts

1. Introduction

Significant changes in the Earth's climate have been observed during the previous century, and a large component of these changes is attributable to anthropogenic sources (IPCC 2007). Projections of climate change are largely informed by simulations using Atmosphere–Ocean General Circulation Models (AOGCMs) which are subject to uncertainty not only in their representation of the physical system, but also in the future boundary conditions which are partly dependent on the future development of human society. Characterizing this uncertainty requires a range of representative scenarios to be devised assuming a range of economic and technological development pathways, population growth and climate mitigation strategies, such as those summarized in the Special Report on Emission Scenarios (SRES, Nakićenović *et al* 2000) and more recently the Representative Concentration Pathways

(RCPs, Moss *et al* 2010) devised for the CMIP-5 suite of experiments.

Recent studies have explored the lower bound for feasible emission pathways. The lowest of the four RCPs, RCP-2.6, is based on a scenario from the IMAGE integrated assessment model (van Vuuren *et al* 2006) and implies forcing that peaks just above 3 W m^{-2} near mid-century and then declines to 2.6 W m^{-2} in 2100. This scenario includes carbon emissions that peak around 2020 and become negative by 2070. Uncertainty over the feasibility of this type of emissions pathway stimulated a number of additional studies, including an explicit analysis of whether the RCP-2.6 could be replicated in other models (Weyant *et al* 2009). In addition, the political goal of preventing global average temperature from increasing more than 2°C relative to pre-industrial, which appears in the Copenhagen Accord signed to date by 139 countries, has motivated a number of analyses of the feasibility of very low emissions scenarios (den Elzen *et al* 2007, O'Neill *et al* 2010) and their climate consequences (Meinshausen *et al* 2009,

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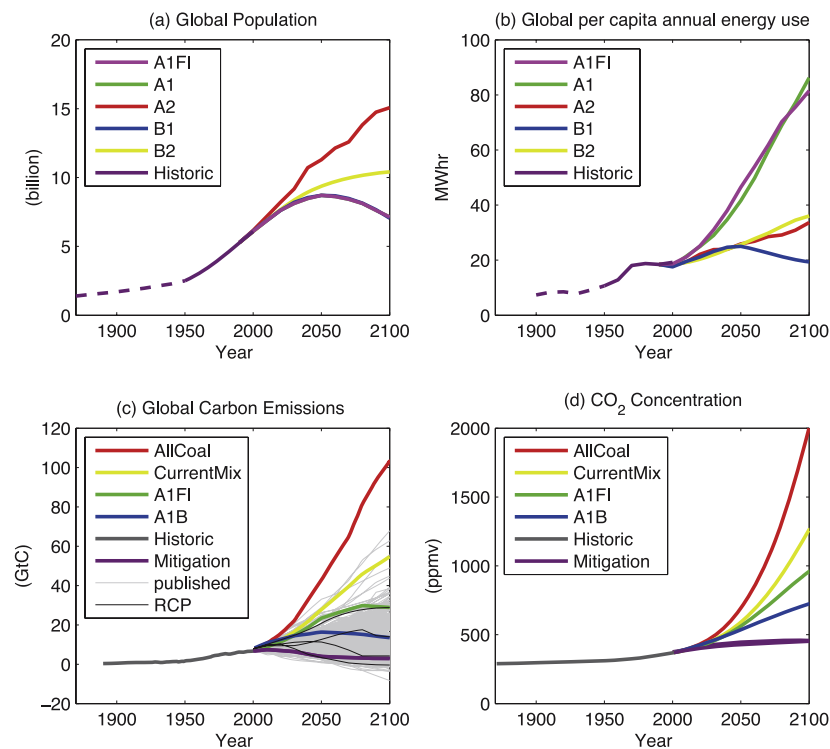


Figure 1. (a) Mean global population trajectories for the representative scenarios used in the SRES report. (b) Global per capita energy use for each of the SRES scenarios, past data from (Krausmann *et al* 2009). (c) Global anthropogenic emissions of CO₂ in the RCP candidates, together with four scenarios considered for this study and the mitigation scenario from Washington *et al* (2009) and 600 published scenarios available at the time of publication. (d) Carbon dioxide concentration pathways calculated using ISAM for each of the scenarios considered in this study and Washington *et al* (2009).

van Vuuren *et al* 2008), including several that are lower than the RCP-2.6.

In contrast, relatively little attention has been paid to the upper bound of the range of future emissions. The highest emission scenario to be used for the upcoming CMIP-5 suite of experiments is RCP 8.5, which is representative of approximately the 90th percentile of published baseline scenarios in terms of emissions of CO₂ from energy use (Moss *et al* 2010) and was based on a revised version of the SRES A2 scenario (Riahi *et al* 2007). This scenario describes a future with no emissions mitigation policy, high energy demand, and continued reliance on fossil fuels. Emissions of CO₂ reach about 27 GtC yr⁻¹ by the end of the century, similar to the A1FI family of scenarios in SRES (see figure 1(c)), which is frequently used as representative of the upper bound of plausible greenhouse gas forcing (e.g., Schneider 2009). However, no explicit scenario analyses, analogous to those exploring the lowest feasible emissions scenarios, have been carried out to test how high emissions might plausibly be in the future.

A growing number of studies are beginning to shift their consideration to consider higher global mean temperatures in the coming century. A recent issue of *Philosophical Transactions of the Royal Society* considered the physical and societal implications of global mean temperatures rising 4 °C above pre-industrial levels, in contrast to the Copenhagen Accord’s commitment to 2 °C (New *et al* 2011). In the same issue, Anderson and Bows (2011) concluded that keeping

global mean temperatures below 2 °C above pre-industrial would require near-instantaneous cuts in emissions for the developed Annex 1 economies, and peaks no later than 2020 for developing Annex 2 economies.

There are reasons to believe that emissions higher than those in the SRES set are, if not likely, at least plausible. First, approximately 10% of the emissions scenarios in the literature have emissions higher than those in the RCP 8.5 (Hanaoka *et al* 2006). Second, a number of studies have noted the substantial shifts in energy intensity and carbon intensity built into the SRES scenarios, arguing that a more realistic baseline may include less optimistic assumptions (Pielke *et al* 2008). And third, independent studies (Schweizer and Kriegler 2011) of the internal consistency of assumptions contained in the SRES scenarios find that scenarios with a heavy reliance on fossil fuels, particularly coal, are under-represented in SRES.

Almost a decade has passed since the publication of the SRES scenarios, so it is therefore of some interest to evaluate global emissions during this period in the context of these scenarios. The International Energy Agency publish annual estimates for greenhouse gas emissions from energy-related sources (Tanaka 2010b), recently quoting a value of 30.6 billion tonnes CO₂ emitted in 2010 (IEA press release, May 2011). This compares closely with the A1FI values for fossil fuel CO₂ emissions of 31.75 billion tonnes CO₂ in 2010. However, this period is too short to constrain any long-term trends in emissions because of significant interannual variability.

The lack of exploration of the upper range of plausible emissions futures is problematic because a key component of decision-making under uncertainty is sufficient attention to the tails of the distribution of possible outcomes (Lempert *et al* 2004). Low likelihood outcomes can critically affect decisions if their consequences are large. It is therefore worthwhile to explore very high (and very low) emissions scenarios with AOGCMs to test their climate change outcomes.

There is also an argument for exploring the climate consequences of emissions scenarios that may appear to be implausible. First, determining the bounds of plausibility is subject to high uncertainty, so a conservative approach would argue for at least testing the outcomes of scenarios that remain within physical constraints, but that otherwise are not much constrained by judgments of plausibility. Second, given the uncertainty in upper bounds for emissions, it is worthwhile to explore the possibility for nonlinear impacts or feedbacks that may occur at high levels or rates of climate change. The existence of possible thresholds for such behavior would be of scientific interest as well as useful context for decision-making. Third, given that a single AOGCM is not typically used to represent uncertainty in climate sensitivity, testing a very high emissions scenario can be a substitute for exploring climate consequences of a lower emissions scenario in a model with a higher (but still plausible) sensitivity to radiative forcing.

We therefore present two hypothetical CO₂ emissions trajectories in which future emissions are considerably greater than those considered in the A1FI family of scenarios. We then use these scenarios to drive full AOGCM simulations for the next century to determine global and regional climate impacts. The focus of this study is primarily to investigate the response of the GCM to very large greenhouse gas forcing, and therefore we keep our emissions scenarios intentionally simple. Section 2 describes these scenarios. Section 3 describes the climate model simulations, including a comparison to a simulation with CCSM 3.0 of climate outcomes under an aggressive mitigation scenario (Washington *et al* 2009). Section 4 concludes.

2. Very high emissions scenarios

We specify two high CO₂ emissions scenarios based on a combination of three assumptions: future global population growth, per capita primary energy demand, and the fuel mix of primary energy supply. We use existing, plausible projections of population and per capita energy, and combine them with illustrative assumptions about future energy supply. In both cases, emissions of all other greenhouse and non-greenhouse gases are kept at the A1FI levels. Our approach is intentionally simple, designed to produce easily interpreted benchmark emissions projections as thought experiments, suitable for exploring the consequences of very high forcing with a climate model. They are not intended as fully articulated scenarios of socio-economic development and energy system evolution.

Our first scenario adopts the global per capita primary energy outcome of the SRES A1FI scenario, which is the highest of the SRES scenarios in terms of this variable (see figure 1(b)). We combine this projection with the UN medium population projection assumed in the SRES B2 scenario

(figure 1(a)), which foresees an increase from 6 billion people in 2000 to about 11 billion by the end of the century. Although the A1FI scenario assumes population follows the UN low projection, in which population peaks and then declines to about 5.5 billion by 2100, uncertainty in the relation between population growth, economic factors, and energy use allows for considerable flexibility in matching population pathways to other scenario elements. In addition, we assume that the shares of primary energy derived from different fuel sources remains fixed over time at 2000 levels (figure 2); that is, the carbon intensity of energy supply is assumed to remain constant. The implications for emissions of such ‘frozen carbon intensity’ assumptions have been previously explored (Fisher *et al* 2007) and are similar, although not identical, to so-called ‘frozen technology’ assumptions (Fisher *et al* 2007, Pielke *et al* 2008) that keep the energy intensity of GDP constant as well.

Due to the higher total energy demand and carbon intensity in our scenario, emissions are about double those in A1FI by the end of the century, reaching about 55 GtC yr⁻¹ by 2100. This emissions level is similar to the highest nonintervention emissions scenarios in existing published literature (Khanna and Chapman 2001, Mori 2003, Tol 2006). Most of the difference relative to A1FI is a result of higher energy demand created by a larger population, with about 40% due to the assumption of fixed carbon intensity. Although A1FI is a fossil intensive scenario, it still shows some shift toward low carbon energy, with over 30% of primary energy obtained from carbon neutral sources in 2100 (compared to 14% in 2000). Our frozen carbon intensity assumption is intended to be a convenient means of representing a future in which the reliance on fossil fuels is heavier than it is in A1FI.

In our second scenario, we make more extreme assumptions. We maintain the A1FI per capita energy projection, but assume population follows the UN high scenario as implemented in the A2 scenario, reaching 15 billion by 2100. We also assume that energy supply increases in carbon intensity over time rather than remaining constant. We make the bounding assumption that all new demand for primary energy is satisfied by coal (figure 2), the fossil fuel with the highest amount of carbon per unit of energy. This assumption is not intended to represent a plausible future, but a useful thought experiment that could help inform the exploration of upper bounds on emissions. It is astounding, for example, that this combination of assumptions leads to emissions in 2100 that are about four times those in the A1FI scenario, or about 105 GtC yr⁻¹ (figure 1(c)).

It can be easily argued that such an emissions scenario is outside the realm of possibility, but the resulting atmospheric CO₂ concentrations in the scenario cannot be so quickly disregarded, given the possibility of a large, unknown feedback in the carbon cycle. Hence, one could interpret the CO₂ concentration pathway in this scenario as one achieved not by anthropogenic emissions alone, but by anthropogenic emissions plus an unforeseen feedback (Meehl *et al* 2007). Coupled climate-carbon models are in their infancy and are subject to considerable structural and parametric uncertainty (Huntingford *et al* 2009), so consideration of unknown feedbacks is prudent when exploring possible upper bounds.

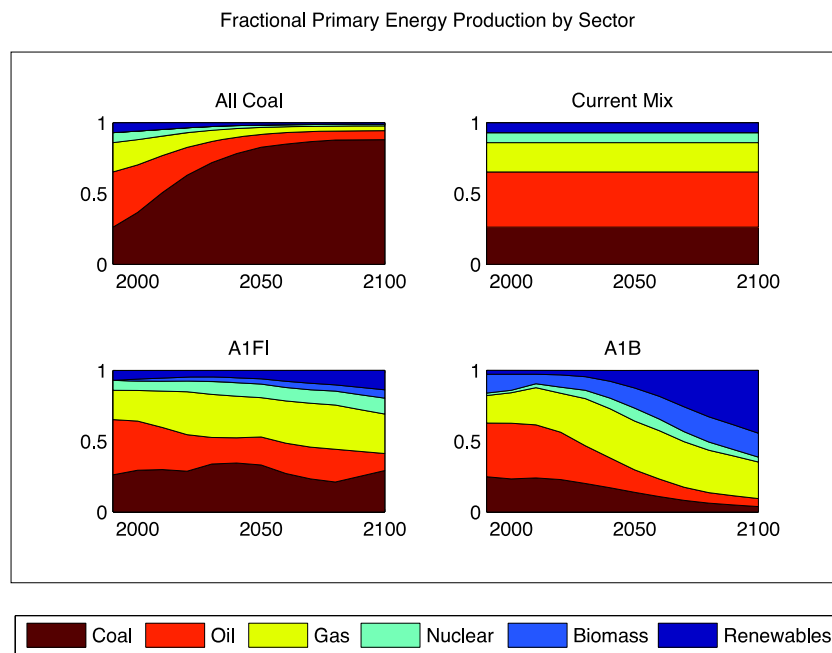


Figure 2. Area plots showing fractional global primary energy sources as a function of time for the next century under four scenarios—A1FI and A1B marker scenarios from SRES, together with two hypothetical high emission scenarios devised for this study.

Although these scenarios are proposed as thought experiments, it is nevertheless of interest to consider estimates of the availability of fossil fuels for the next century which could provide physical constraints on resource use. Figure 3 shows the cumulative consumption of resources in each of the scenarios considered in this study. Estimates of fossil fuel reserves are highly uncertain, but Sims *et al* (2007) provide some estimates of currently proven resources, together with estimates of likely future discoveries based upon historical experience in geological basins.

The A1B scenario consumes 70% of proven coal reserves by the end of the century, where ‘proven reserves’ are defined as those that are known to exist and that can be recovered using current technologies and under current conditions, including prices. In contrast, A1FI and CurrentMix consume about 125% of probable reserves, a category containing coal that is less certain to be recoverable. The AllCoal scenario uses considerably more resource, using 135% of all possible coal reserves by 2100, where ‘possible reserves’ refers to those with large uncertainty in whether they will be recoverable. Clearly, resources will demand a higher price as they become more scarce, so reserves which are not currently economically feasible to mine will become so in the future.

For oil usage, only two of the scenarios (AllCoal and A1B) use less than current estimates of all sources of oil by the end of the century, but even these require the use of unconventional sources such as shales, heavy oils and tar sands. This remains an issue of great debate with a recent study (Kerr 2011) even proposing the possibility that peak conventional oil production has already occurred. The A1FI scenario assumes that 130% of all possible conventional and unconventional oil reserves will be consumed by 2100, while the CurrentMix scenario would require 300% (although in practice coal-based liquid fuels could supplement oil toward the end of the century). In

the case of natural gas, three of the scenarios (A1B, A1FI and CurrentMix) can only be achieved with unconventional reserves such as tight gas sands, fractured shales, coal beds and hydrates, while it is likely that the natural gas necessary for the AllCoal scenario is within existing reserves.

3. Simulations

3.1. Model

The climate simulations which follow are conducted using the Community Climate System Model version 3.0 (CCSM3) (Collins *et al* 2006, Meehl *et al* 2005), a full global climate model with interactive atmospheric, ocean, land/vegetation (prescribed), and sea-ice components. These simulations use a T42 spectral resolution (approximately 2.8° by 2.8°) in the atmosphere and less than 1° horizontal resolution in the ocean, and do not require flux adjustments. The simulations are all branched from a 20th century CCSM simulation. The A1B and A1FI scenarios are as defined by SRES. The CO₂ emissions for the CurrentMix and AllCoal scenarios are described in section 1, with all other concentration pathways identical to A1FI.

To calculate global CO₂ concentrations from the emissions pathway, we use the Integrated Science Assessment Model 2.5D (ISAM) described in Jain and Cao (2005) and Cao and Jain (2005). The model is tuned such that the climate sensitivity was equal to that of CCSM 3.0 (Kiehl *et al* 2006). The concentration pathways for each simulation conducted in this study are plotted in figure 1(c). Using this approach, we find the ‘CurrentMix’ scenario achieves a CO₂ concentration of 1230 ppmv by the end of the century, while the ‘AllCoal’ simulation has a concentration of 2000 ppmv.

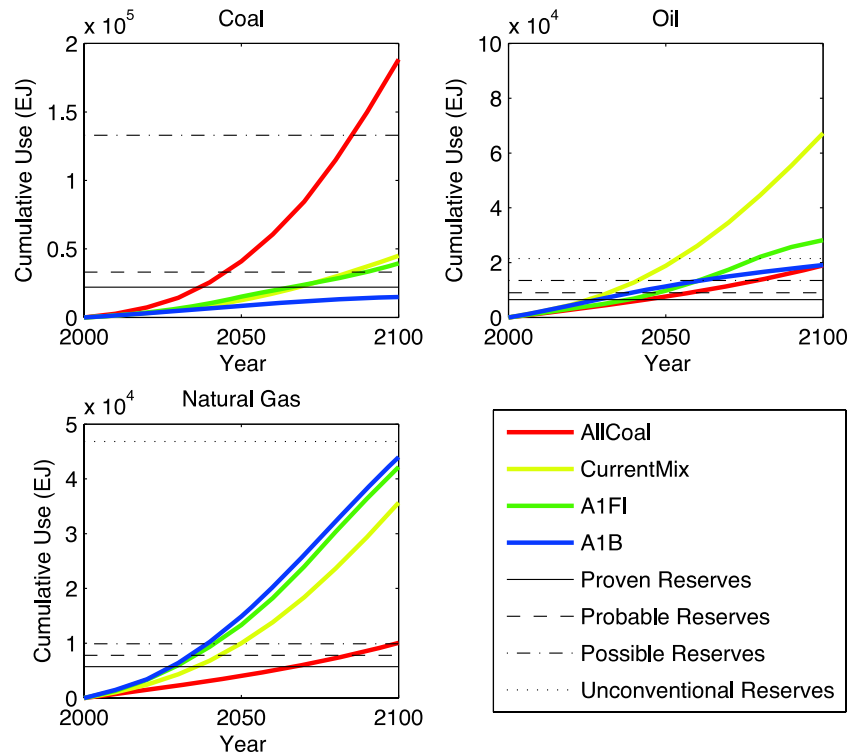


Figure 3. Cumulative resource use for coal, oil and natural gas in ExaJoules as a function of time for the 21st century, together with current estimates of fossil fuel reserves reproduced from Sims *et al* (2007). Colored lines show the cumulative resource use for each 21st century scenario considered, while horizontal lines show reserve estimates. Proven reserves (solid black) are verified, economically viable sources which currently exist. Probable (dot-dash) and possible (dashed) resources are based on historical experience in geological basins. Unconventional (dotted) sources are those which are currently not economically viable, but may become so in the future such as oil from shales, heavy oils and tar sands and natural gas from tight gas sands, fractured shales, coal beds and hydrates.

3.2. Results

The time-series of global mean temperature shows that major differences between the scenarios only begin to materialize in the latter part of the 21st century (figure 4(a)). In 2030, the four scenarios are indistinguishable when compared to the interannual variability. In 2050, there is some apparent distinction; A1B shows a 1 K warming above 1990 levels, A1FI and CurrentMix show a 1.3 K warming while the AllCoal scenario shows a 1.7 K warming. However, by 2100 the differences are significantly more pronounced; the A1B and A1FI scenarios show warming of 2.2 and 2.9 K respectively, while CurrentMix shows a 3.7 K warming and AllCoal warms by 5.1 K above 1990 levels. Only the Washington *et al* (2009) mitigation scenario shows a negative trend in global mean temperatures at the end of the century, with 2100 temperatures of 0.8 K above 1990 levels.

We do not find a significant change in the global effective climate sensitivity of CCSM 3.0 at very large CO₂ concentrations, and in each of the high emissions scenarios CurrentMix and AllCoal, the global mean temperatures calculated by the simple ISAM model remains consistent with the CCSM result. The ISAM model does predict slightly higher CO₂ concentrations for the Washington *et al* (2009) emissions than were obtained with the MAGICC simulation used in the original study, which results in slightly higher end-of-century temperatures.

In order to test the long-term global mean behavior in these scenarios, we also show ISAM integrations out to 2500. These simulations make the assumption that the effective climate sensitivity of the system does not increase during this period. Although we do not test this assumption here, a separate study (Sanderson, in preparation) investigates the state-dependence of the climate sensitivity in the CCSM up to much larger CO₂ concentrations and finds an assumption of constant climate sensitivity is reasonable up to at least eight times pre-industrial values in the community atmosphere model.

In the extended ISAM simulations, we show two illustrative bounding cases starting from 2100 conditions in each of the scenarios defined above. For the lower bound, we show the commitment warming and sea level rise observed when emissions are reduced to zero at 2100. In this case, the high emission scenarios AllCoal, CurrentMix and A1FI show approximately 1 K cooling in global mean temperatures between 2100 and 2500, A1B shows 0.2 K cooling and mitigation scenario is approximately stable. For the upper bound, we maintain emissions at 2100 levels indefinitely. This is clearly a hypothetical scenario, given the finite availability of fossil fuels, however, the CurrentMix scenario could achieve 10 K warming above 1990 levels by 2500 if emissions levels were maintained, while the AllCoal scenario shows almost 12 K warming. Even the A1B scenario would achieve 5.5 K warming by 2500 if 2100 emissions levels were maintained.

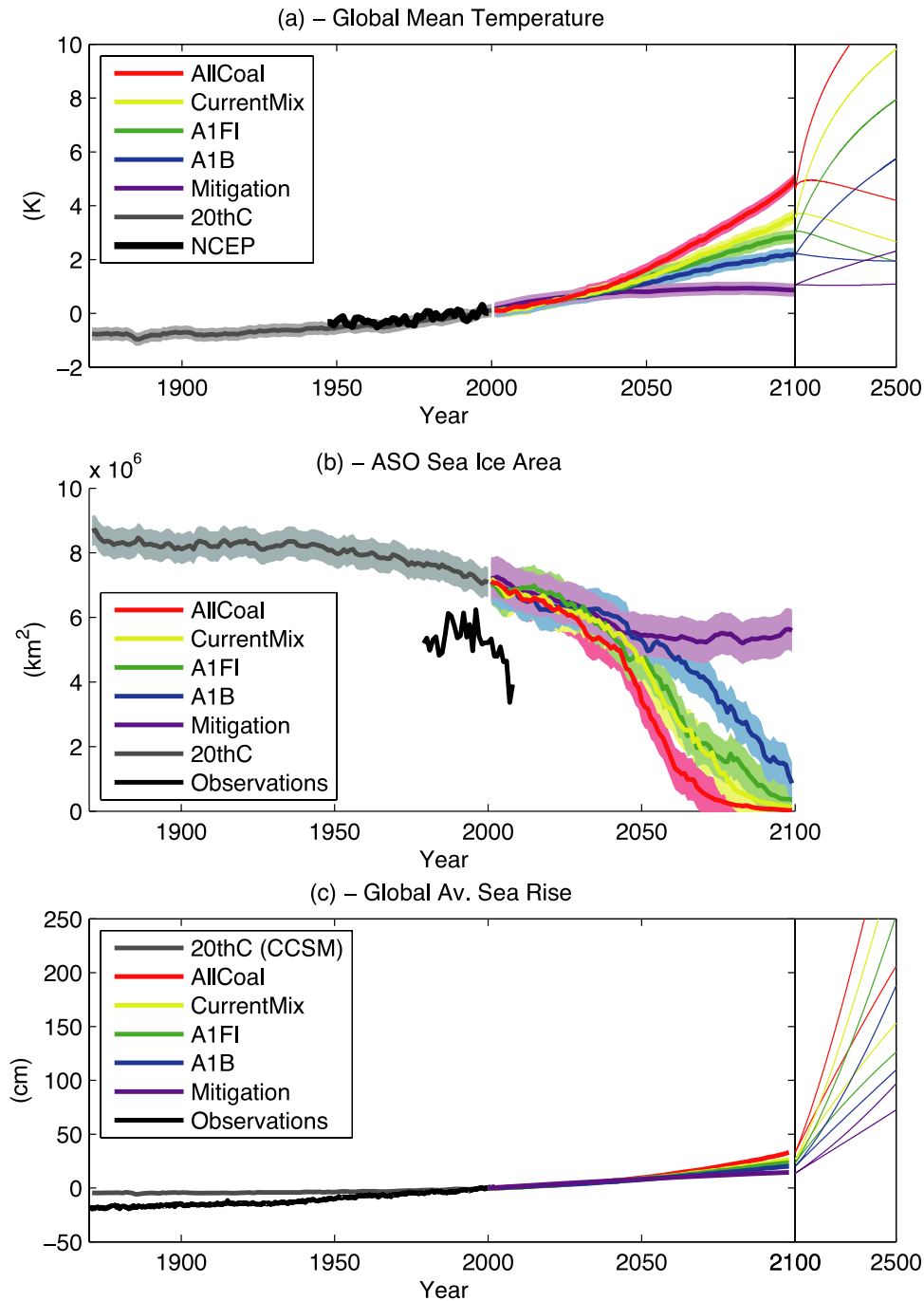


Figure 4. (a) Time-series for CCSM simulations of global mean temperatures, (b) August–September–October mean Arctic Sea-Ice area and global average sea level rise (thermal expansion only) for the high emission scenarios plus SRES and the mitigation scenario from Washington *et al* (2009). Post-2100 data shows ISAM output for both constant 2100 emissions and zero emissions. Observational estimates shown in black include surface temperature reanalysis data taken from NCEP, Arctic Sea-Ice area observations taken from SMMR, SSM/I data (from the National Sea-Ice Data Center) and sea level rise observations reproduced from Church and White (2006). Time-series are plotted with a 5 year low-pass filter, with the standard deviation of higher frequency noise shown by colored shading.

The geographical distribution of warming (figure 5(a)) shows a similar pattern for each of the scenarios considered, amplified for the higher emission scenarios. Both the CurrentMix and AllCoal scenarios simulate warming of over 12 K in arctic regions by 2100, with a complete absence of summer sea-ice (figure 4(b)). The AllCoal scenario shows 90% Arctic sea-ice loss in the minimum extent months of August through October (ASO) by 2060, compared with

2075 for the CurrentMix simulation and 2085 for A1FI (in contrast, the mitigation scenario stabilizes at 75% of 1990 ASO sea-ice extent in 2050, and shows some slight recovery by the end of the century). Arctic warming is greatest in fall and winter (figure 6), as decreased sea-ice cover leads to increased absorbed solar radiation which further thins sea-ice and leads to much warmer winter temperatures. In contrast, summer temperatures increase much less, as melting

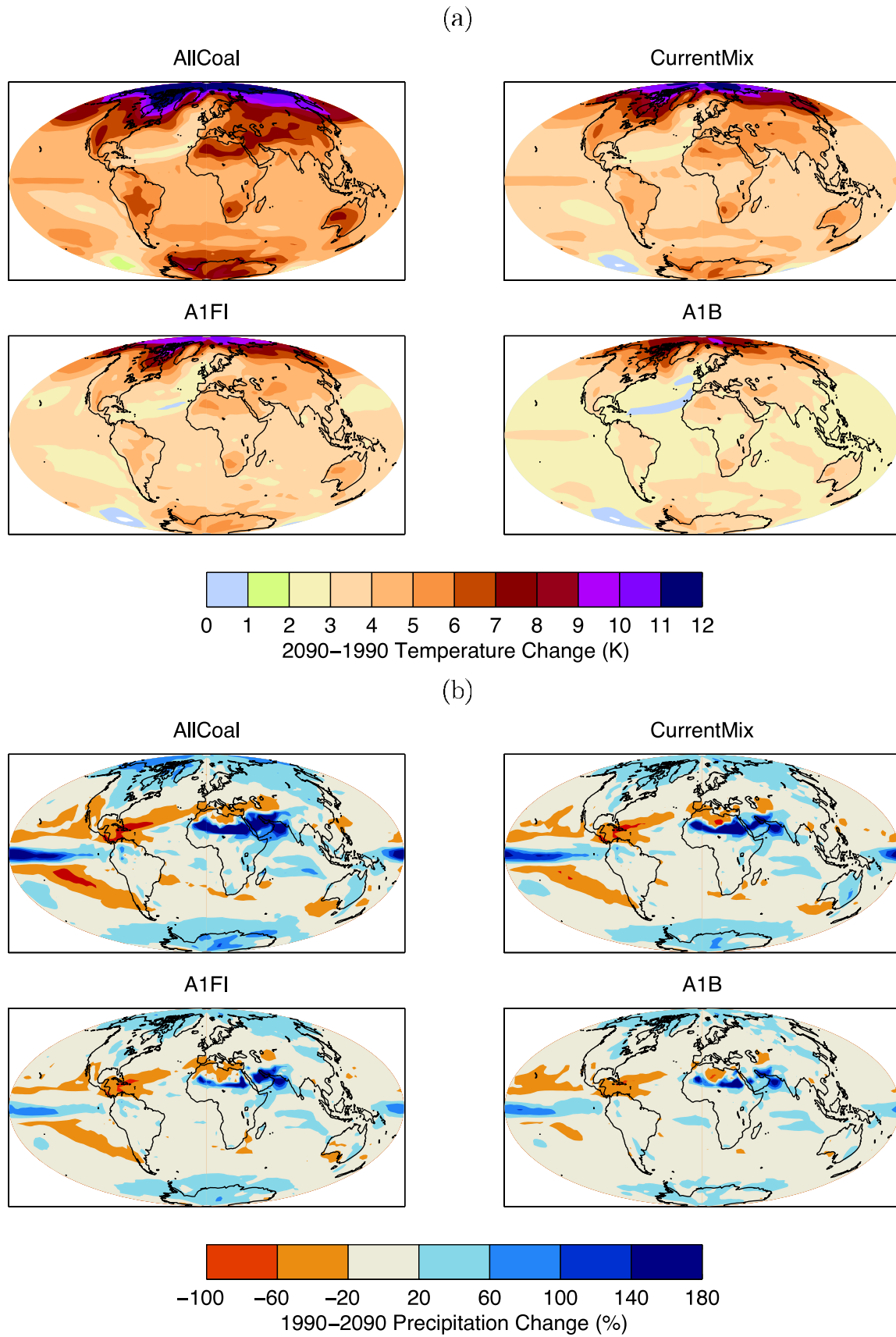


Figure 5. (a) Surface temperature change in Kelvin for the end of the 21st century, showing 2080–100 means minus the reference 1980–2000 period. (b) percentage precipitation change for 2080–100 relative to 1980–2000 levels. All maps are generated with output from CCSM3.0.

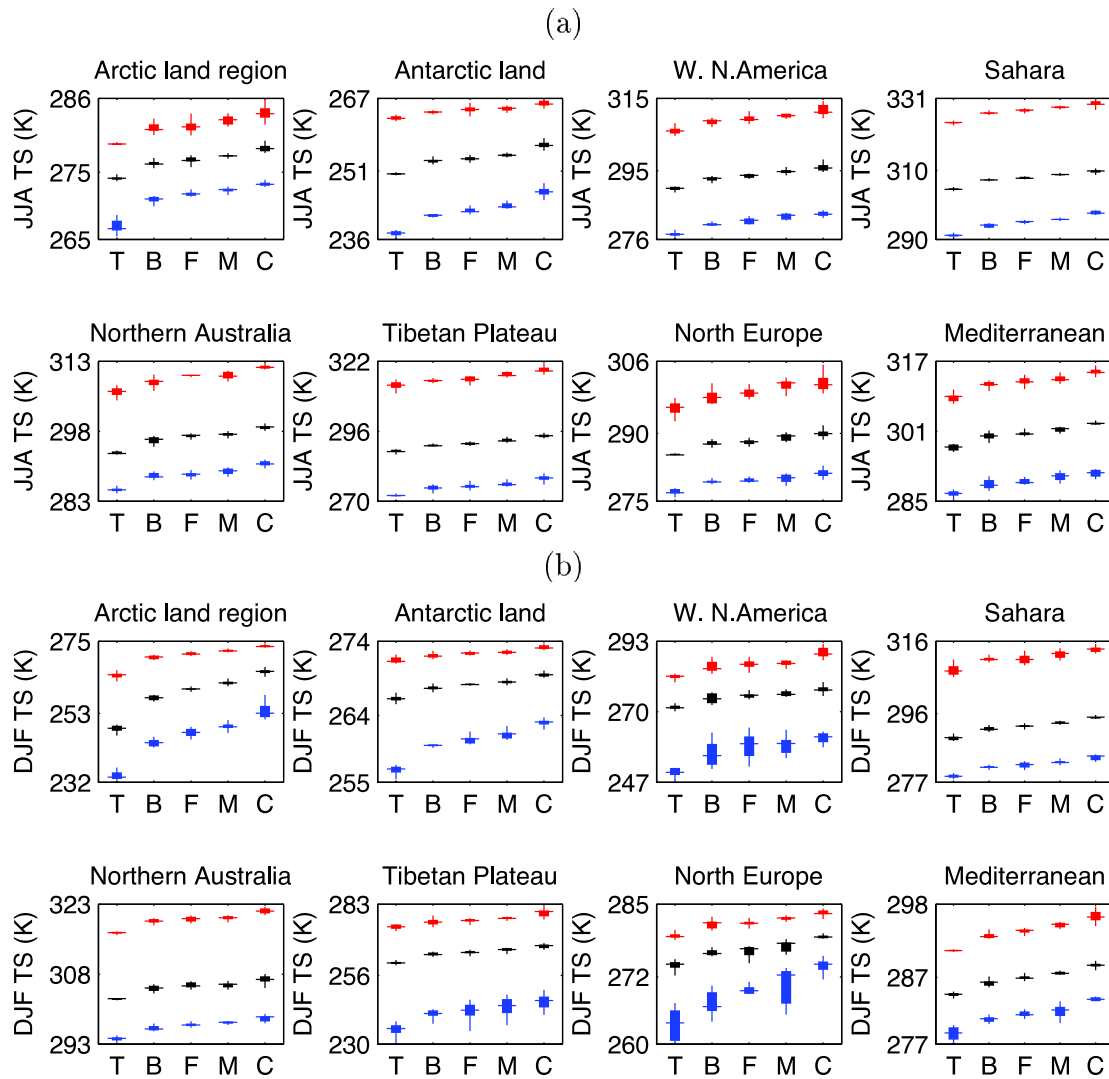


Figure 6. Regional (a) DJF and (b) JJA temperatures area averaged over regions as defined in Giorgi and Francisco (2000). Distributions show CCSM surface temperature output in Kelvin for the late 20th century 1980–2000 (T), and 2080–100 for each scenario A1B (B), A1FI (F), CurrentMix (M) and AllCoal (C). For each region, the black box-whisker plot shows the seasonal mean temperature distribution, the boxes extend to the 75th percentiles and the whiskers to the extreme values. The distribution of seasonal maximum and minimum temperatures are shown in red and blue respectively (the temperatures thus represent a time mean over a single 20 min model time-step in which the extreme temperature is recorded).

sea-ice keeps surface temperatures near freezing (Walsh and Timlin 2003). The region also shows proportionally larger precipitation increases in both the Arctic and Antarctic in the late 21st century for the higher emission scenarios as compared to the reference A1B case with a 80–120% increase in Arctic precipitation over 1990 levels in the AllCoal scenario (figures 5(b) and 7).

Sea level rise between 1990 and 2100 due to thermal expansion of the oceans for the AllCoal scenario is 33 cm, compared to 27 cm in CurrentMix, 23 cm in A1FI and 20 cm in A1B (figure 4(c)). These figures do not include contributions from melting ice-sheets, where recent evidence suggests that accelerated glacial melt is already apparent (Joughin *et al* 2008) and would continue for several centuries after stabilization of greenhouse gases (Meehl *et al* 2005). The simplified ISAM estimate of sea level rise predicts that the thermal inertia of the oceans would allow sea level rise at a

similar rate for several centuries after 2100 even under constant greenhouse gas concentrations with almost 250 cm of rise in 2500 relative to 1990 levels in the AllCoal scenario, compared with 125 cm sea level rise in 2500 for the A1B scenario.

Land areas of the northern hemisphere tend to show temperature increases of 4–8 K in the AllCoal scenario in comparison to 2–3 K in the reference A1B scenario by 2100, relative to 1990 temperatures. Significant amplification is apparent in arid regions, such as the Western US, the Sahara, the Middle East and Western Australia. Mid-latitude SSTs increase by between 2 and 5 K in the AllCoal scenario compared to 0.5–2 K in the A1B scenario—with uniform warming throughout the seasons (figures 5(a) and 6).

Extremes of temperature are considerably enhanced in the high emission scenarios over the A1B scenario. Most regions show that maximum temperatures by 2100 in the AllCoal scenario increase by a factor of two more than the A1B

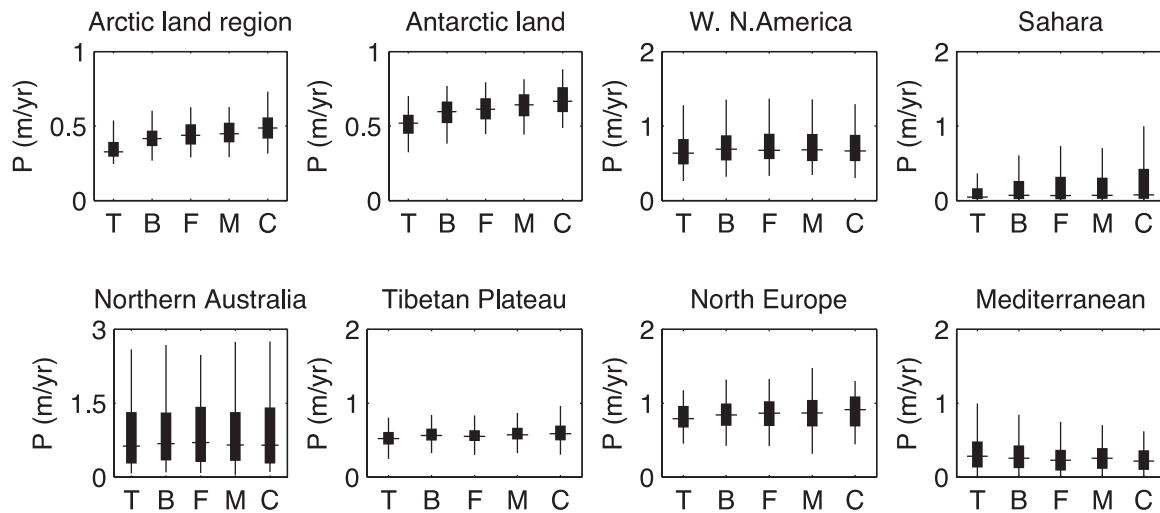


Figure 7. As for figure 6, but values are shown for annual precipitation in meters per year.

scenario, but some regions show considerably more than this. For example, summer (JJA) maximum temperatures in 2100 in both Western North America and North Europe increase by 1.5 K above 1990 levels in the A1B scenario, but by 6 K in the AllCoal scenario (figure 6(b)).

Precipitation changes follow the same general pattern in each of the scenarios, with amplification of the pattern for higher emission scenarios (figure 5(b)). In all scenarios we see the typical pattern of moistening high latitudes and drying subtropics as higher temperatures allow greater poleward moisture transport. These effects, along with increasing precipitation over the inter-tropical convergence zone, scale with increasing CO₂ concentrations at the end of the 21st century, as one would expect from a basic consideration of humidities permitted by the Clausius–Clapeyron relation (Clapeyron 1834, Clausius 1857).

The AllCoal scenario shows 30–80% precipitation reduction from late 20th Century levels in Southern Europe, Central America, Southern Andes, Northern Middle East, Southern Australia and over oceanic subtropical regions. Precipitation increases of 50–200% are seen in Arctic and Antarctic regions, Northern Canada, Siberia, Northern Africa, the Southern Middle East and in the equatorial Pacific. High latitude show precipitation increases scale with CO₂ concentrations, such that in the A1B scenario shows changes of 1/3 the magnitude of those in the AllCoal scenario. Subtropical drying, such as that in the Caribbean also scales with CO₂ concentrations. However, in some tropical regions, precipitation increases appear to saturate (for example, the Amazon basin shows a 20% increase in precipitation in all future scenarios considered here).

The strong dipole Mediterranean drying and Saharan wetting has been explained by increased divergence over the Mediterranean, combined with increased humidity allowed by Clausius–Clapeyron and soil moisture drying due to increased evaporation in Southern Europe (Mariotti *et al* 2008). An increased land–sea temperature difference enhances the mean flow of moist air from the Mediterranean to Northern Africa

with a resultant increase in precipitation. We find that the amplitude of this dipole pattern is also proportional to end-of-century CO₂ concentrations and much of the additional rainfall over Northern Africa is due to extreme high rainfall events, in agreement with previous studies (Allen and Ingram 2002).

4. Conclusions

We have proposed two hypothetical global emissions scenarios for the coming century which test the sensitivity of the Community Atmosphere Model to CO₂ concentrations significantly greater than those seen in the scenarios considered in the Fourth or Fifth Assessment Report of the IPCC. The purposes of this were both to test the linearity of the response to a large greenhouse gas forcing (an assumption often made in simple models of climate used in integrated assessment), and to explore in an idealized fashion the upper bound on future anthropogenic emissions over the next century. Our simulations take per capita energy demand from the A1FI scenario, but assume slightly greater population growth and higher carbon intensity; one simulation assumes that fractional primary energy production remains at present day values while the other more extreme scenario assumes that all future energy demand is met by coal.

Our results show global and regional climate changes associated with these very high emissions scenarios are substantially greater than the A1FI scenario—which represents the upper bound of emissions for 2100 of the scenarios considered for the Fourth Assessment Report. The ‘CurrentMix’ and ‘AllCoal’ scenarios would imply 2100 global mean temperatures of 0.5 and 1.2 K greater than A1FI, although we find no evidence for a temperature dependency of global climate sensitivity within the range of forcing scenarios considered here, with global mean temperatures remaining approximately consistent with those predicted by the ISAM model which assumes a constant value for climate sensitivity.

Clearly the results of this study are subject to systematic and parametric uncertainties in the climate model used.

CCSM3.0 has a climate sensitivity of 2.7 K and a transient climate response of 1.5 K compared to CMIP3 means of 3.2 and 1.9 K respectively, which might suggest that global mean temperature response in CCSM is under representative of the multi-model consensus. However, in the SRES A1B scenario, the CCSM3 simulation is more representative of the ensemble mean, with a 2100 warming of 2.7 K above pre-industrial temperatures compared to the CMIP3 mean of 2.8 K, suggesting a cancellation of effects where the CCSM response to negative aerosol forcing may also be less than the CMIP3 mean.

The high emissions scenarios considered here assume that aerosol and sulfate forcing remains the same as that in A1FI, primarily because the focus of this study is on model response to large net climate forcings. In reality, depending on the dominant energy source, there would likely be significant increases in aerosol concentrations in the two high emissions futures proposed—especially in the hypothetical AllCoal case. Higher sulfate concentrations would likely act to compensate to some of the greenhouse gas forcing, although the degree of compensation remains somewhat uncertain and model dependent (Forster *et al* 2007).

Even using a model such as CCSM3.0, with a relatively low transient climate response to CO₂ increase, very significant changes in climate can be seen by 2100, with regional mean changes generally scaling with the greenhouse gas forcing at the end of the century, although some regions such as the western USA, the Tibetan Plateau and Northern Europe exhibit strong local positive temperature feedbacks which enhance local temperature gain relative to the global mean in the very high emission scenarios. The AllCoal scenario shows a complete loss of September Arctic sea-ice some 20 years before the A1FI scenario, and almost 50% greater global sea levels than A1FI relative to 1990 levels by 2100. Patterns of precipitation change remain similar throughout the range of scenarios considered here, but the amplitude of those patterns increases in the very high emissions scenarios. The AllCoal scenario shows over 50% reduction in net precipitation in the western USA, the Mediterranean and central America, and over 100% increase in Northern Africa, and most regions polewards of 60° North or South.

In 2010, global CO₂ emissions were 96% of those found in the A1FI scenario. The scenarios considered here are not intended to be politically, economically or technically plausible; we leave it to further study to construct self-consistent future high emission scenarios. However, the findings in this study serve to show that a future in which emissions continue exceed the full range of SRES scenarios would result in significant additional climate changes above those described in the simulations considered in the Fourth Assessment Report. Although these simulations reveal no significant nonlinearities in global climate feedbacks, the model used is not capable of simulating the biogeophysical elements of the Earth system which are the most likely candidates for large nonlinearities in response to increasing emissions. A next logical step is therefore to repeat experiments of this type using a next-generation model with a fully interactive carbon cycle.

Acknowledgment

This research was supported by the Office of Science (BER), US Department of Energy.

References

- Allen M R and Ingram W J 2002 Constraints on future changes in climate and the hydrologic cycle *Nature* **419** 224–32
- Anderson K and Bows A 2011 Beyond dangerous climate change: emission scenarios for a new world *Phil. Trans. R. Soc. A* **369** 20
- Cao L and Jain A 2005 An Earth system model of intermediate complexity: simulation of the role of ocean mixing parameterizations and climate change in estimated uptake for natural and bomb radiocarbon and anthropogenic CO₂ *J. Geophys. Res.—Ocean* **110** C09002
- Church J and White N 2006 A 20th century acceleration in global sea-level rise *Geophys. Res. Lett.* **33** L01602
- Clapeyron E 1834 Memoir on the motive power of heat *J. l'Ecole Polytechn.* **14** 153–90
- Clausius R 1857 On the nature of the motion which we call heat *Phil. Mag.* **14** 108–27
- Collins W D *et al* 2006 The Community Climate System Model version 3 (CCSM3) *J. Clim.* **19** 2122–43
- den Elzen M, Meinshausen M and van Vuuren D 2007 Multi-gas emission envelopes to meet greenhouse gas concentration targets: costs versus certainty of limiting temperature increase *Glob. Environ. Change* **17** 260–80
- Fisher B *et al* 2007 Issues related to mitigation in the long term context *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed B Metz, O R Davidson, P R Bosch, R Dave and L A Meyer (Cambridge: Cambridge University Press)
- Forster P *et al* 2007 Changes in atmospheric constituents and in radiative forcing *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon *et al* (Cambridge: Cambridge University Press)
- Giorgi F and Francisco R 2000 Uncertainties in regional climate change prediction: a regional analysis of ensemble simulations with the hadcm2 coupled aogcm *Clim. Dyn.* **16** 169–82
- Hanaoka T, Kawase R, Kainuma M, Matsuoka Y, Ishii H and Oka K 2006 *Greenhouse Gas Emissions Scenarios Database and Regional Mitigation Analysis* (Tsukuba: NIES)
- Huntingford C, Lowe J A, Booth B B B, Jones C D, Harris G R, Gohar L K and Meir P 2009 Contributions of carbon cycle uncertainty to future climate projection spread *Tellus B* **61** 355–60
- IPCC 2007 *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon *et al* (Cambridge: Cambridge University Press)
- Jain A and Cao L 2005 Assessing the effectiveness of direct injection for ocean carbon sequestration under the influence of climate change *Geophys. Res. Lett.* **32** L09609
- Joughin I, Das S B, King M A, Smith B E, Howat I M and Moon T 2008 Seasonal speedup along the western flank of the Greenland ice sheet *Science* **320** 781–3
- Kerr R 2011 Peak oil production may already be here *Science* **331** 1510
- Khanna N and Chapman D 2001 Energy efficiency and petroleum depletion in climate change policy *The Long-Term Economics of Climate Change: Beyond a Doubling of Greenhouse Gas*

- Concentrations* ed D C Hall and R B Howard (Greenwich, CT: JAI Press)
- Kiehl J, Shields C, Hack J and Collins W 2006 The climate sensitivity of the Community Climate System Model version 3 (CCSM3) *J. Clim.* **19** 2584–96
- Krausmann F, Gingrich S, Eisenmenger N, Erb K, Haberl H and Fischer-Kowalski M 2009 Growth in global materials use, GDP and population during the 20th century *Ecol. Econ.* **68** 2696–705
- Lempert R, Nakicenovic N, Sarewitz D and Schlesinger M 2004 Characterizing climate-change uncertainties for decision-makers. An editorial essay *Clim. Change* **65** 1–9
- Mariotti A, Zeng N, Yoon J-H, Artale V, Navarra A, Alpert P and Li L Z X 2008 Mediterranean water cycle changes: transition to drier 21st century conditions in observations and CMIP3 simulations *Environ. Res. Lett.* **3** 044001
- Meehl G, Washington W, Collins W, Arblaster J, Hu A, Buja L, Strand W and Teng H 2005 How much more global warming and sea level rise? *Science* **307** 1769
- Meehl G *et al* 2007 Global climate projections *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon *et al* (New York: Cambridge University Press) pp 747–845
- Meinshausen M, Meinshausen N, Hare W, Raper S C B, Frieler K, Knutti R, Frame D J and Allen M R 2009 Greenhouse-gas emission targets for limiting global warming to 2 °C *Nature* **458** 1158–62
- Mori S 2003 Energy and technology strategies in long-term global views: simulations of the integrated assessment model MARIA *International Frameworks and Technological Strategies to Prevent Climate Change* pp 205–22
- Moss R *et al* 2010 The next generation of scenarios for climate change research and assessment *Nature* **463** 747–56
- Nakićenović N *et al* 2000 *IPCC Special Report on Emissions Scenarios (SRES)* (Cambridge: Cambridge University Press)
- New M, Liverman D, Schroder H and Anderson K 2011 Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications *Phil. Trans. R. Soc. A* **369** 6
- O'Neill B, Riahi K and Keppo I 2010 Mitigation implications of mid-century targets that preserve long-term climate policy options *Proc. Natl Acad. Sci. USA* **107** 1011–6
- Pielke R, Wigley T and Green C 2008 Dangerous assumptions *Nature* **452** 531–2
- Riahi K, Grübler A and Nakicenovic N 2007 Scenarios of long-term socio-economic and environmental development under climate stabilization *Technol. Forecast. Soc. Change* **74** 887–935
- Sanderson B 2011 On the state-dependence of climate sensitivity in a general circulation model (in preparation)
- Schneider S H 2009 The worst case scenario *Nature* **458** 1104–5
- Schweizer V J and Kriegler E 2011 Using cross-impact balance analysis to improve future emissions scenarios *Clim. Change* submitted
- Sims R *et al* 2007 Energy supply *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
- Tanaka N 2010a *CO₂ Emissions from Fuel Combustion* (International Energy Agency)
- Tanaka N 2010b *World Energy Outlook 2010* (International Energy Agency)
- Tol R S J 2006 Multi-gas emission reduction for climate change policy: an application of FUND *Energy J.* **11** 235–50
- van Vuuren D P, Eickhout B, Lucas P L and den Elzen M G J 2006 Long-term multi-gas scenarios to stabilise radiative forcing—exploring costs and benefits within an integrated assessment framework *Energy J.* **27** 201–33
- van Vuuren D *et al* 2008 Temperature increase of 21st century mitigation scenarios *Proc. Natl Acad. Sci.* **105** 15258
- Walsh J and Timlin M 2003 Northern hemisphere sea ice simulations by global climate models *Polar Res.* **22** 75–82
- Washington W M, Knutti R, Meehl G A, Teng H, Tebaldi C, Lawrence D, Buja L and Strand W G 2009 How much climate change can be avoided by mitigation? *Geophys. Res. Lett.* **36** L08703
- Weyant J, Azar C, Kainuma M, Kejun J, Nakicenovic N, Shukla P R, La Rovere E and Yohe G 2009 Report of 2.6 versus 2.9 Watts/m² RCPP evaluation panel *Technical Report, Intergovernmental Panel on Climate Change*