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Climate Stabilization at 2°C and Net Zero Carbon Emissions

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Abstract: The goal to stabilize global average surface temperature at lower than 2°C above pre-industrial level has been extensively discussed in climate negotiations. A number of publications state that achieving this goal will require net anthropogenic carbon emissions (defined as anthropogenic emissions minus anthropogenic sinks such as carbon capture and sequestration and reforestation) to be reduced to zero between years 2050 and 2100. At the same time, it is also shown in the literature that decreases of non-CO_2 emissions can significantly affect the allowable carbon budget. In this study, we explore possible emission pathways under which surface warming will not exceed 2°C, by means of emission-driven climate simulations with an Earth System Model of Intermediate Complexity linked to an Economic Projection and Policy Analysis Model. We carried out a number of simulations from 1861 to 2500 for different values of parameters defining the strength of the climate system response to radiative forcing and the strength of the natural carbon sources and sinks under different anthropogenic emission projections. Although net anthropogenic emissions need to be reduced to zero eventually to achieve climate stabilization, the results of our simulations suggest that, by including significant reductions in non-CO_2 emissions, net carbon emissions do not have to be zero by 2050 or even 2100 to meet the 2°C target because of offsets due to the natural carbon sinks in the oceans and terrestrial ecosystems. We show that net anthropogenic carbon emissions falling from today's 9.5 GtC/year to 2.5–7 GtC/year by 2050 and then to 1–2.8 GtC/year by 2100 are consistent with a 2°C target for a range of climate sensitivities (2.0–4.5°C) similar to the IPCC likely range. Changes in the surface temperature beyond 2100 depend on the emission profiles after 2100. For post-2100 carbon emissions decreasing at a rate of about 1.5% per year along with continued decreases in non-CO_2 emissions, our projections indicate that natural ecosystems will be able to absorb enough carbon to prevent surface temperature from rising further. A major reason for our results is that the land and ocean uptake rates are a function of the total atmospheric CO_2 concentration and, due to the very long lifetime of CO_2, this does not decrease anywhere near as fast as the imposed CO_2 emissions. The required mixes of energy technologies and the overall costs to achieve the 2°C target are highly dependent on the assumptions about the future costs of low-carbon and zero-carbon emitting technologies. In all our projections, the global energy system requires substantial transformations in a relatively short time.

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1. Introduction

Climate stabilization requires substantial greenhouse gas (GHG) emission mitigation efforts (IPCC, 2014). While, some studies indicate that limiting global warming to 2°C above pre-industrial will allow avoidance of potentially dangerous climate impacts (Solomon *et al.*, 2011), other studies conclude that this avoidance will require even lower limits to warming (e.g., Hansen *et al.*, 2008). At the same time, some researchers consider the 2°C goal as extremely ambitious, both politically and economically (Victor and Kennel, 2014). Others point out the arbitrary nature of the 2°C target with policymakers treating it as a hard scientific result, while climate scientists treat it partly as a political issue (Jaeger and Jaeger, 2011). Nevertheless, 2°C warming has emerged as a "safe" level in many recent policy discussions (e.g., UNFCCC, 2009; IPCC, 2014: Knutti *et al.*, 2016).

There are several recent studies that looked at the emission profiles required to achieve various climate stabilization levels (e.g., Matthews and Caldeira, 2008; Meinshausen *et al.*, 2009; Webster *et al.*, 2012; Paltsev *et al.*, 2013; Rogelj *et al.*, 2015b; Sanderson *et al.*, 2016). According to these studies, preventing surface warming from exceeding 2°C, while requiring substantial cuts in anthropogenic emissions, can be achieved with net carbon emissions being positive through the end of this century. Moreover, Matthews and Caldeira (2008) and Zickfeld *et al.* (2009) using a temperature tracking approach showed that, for climate sensitivities less than 4°C, surface temperature can be stabilized with net carbon emissions being slightly positive even through year 2500. It should be emphasized that eventually net anthropogenic carbon emissions must be reduced to zero for the climate system to come in to equilibrium, assuming no changes in natural forcing. The IPCC (2014) summarized more than 1,000 scenarios from different modeling groups and concluded that to achieve the 2°C target, net anthropogenic emissions should be reduced by 40 to 70% by 2050 and be near or below zero by 2100.

Discussions of mitigation targets have also focused on the approximately linear relationship between cumulative CO_2 emissions and surface temperature increase described in a number of publications (e.g. Allen *et al.*, 2009; Matthews *et al.*, 2009, 2012; Zickfeld *et al.*, 2009) and summarized by IPCC (2014, see Figure SPM 5b). Specifically, the IPCC (2014) concludes that multiple lines of evidence indicate a strong, consistent, almost linear relationship between cumulative CO_2 emissions and projected global temperature change to the year 2100. The IPCC diagram shows that a cumulative budget for a 50% chance of meeting the 2°C target is about 820 Gigatonnes of carbon (GtC, or 3000 $GtCO_2$). Under current emission trajectories that do not envision substantial climate policy, the 2°C carbon budget will be consumed by around 2040–2050. Based on the IPCC numbers, some researchers (e.g., Rogelj *et al.*, 2015a) argue that even with more aggressive reduction trajectories, net anthropogenic CO_2 emissions should reach zero around 2060–2075, otherwise, the temperature increase will pass the 2°C target. Net anthropogenic emissions here refer to fossil fuel related, industrial and agricultural emissions minus manmade sinks such as bioenergy production with carbon capture and storage and reforestation, but importantly they do not include the natural sinks into oceans and terrestrial systems. At the same time, Rogelj *et al.* (2015b) show that mitigation of non-CO_2 gases can significantly increase allowable carbon budget. Edmonds *et al.* (2013) present economic scenarios that allow achieving the 2°C target without negative carbon emissions.

In this paper we explore different emission pathways leading to the 2°C stabilization target by means of emissions-driven simulations performed with the MIT Integrated Global Systems Model (IGSM) (Sokolov *et al.*, 2009). Our simulations show that if climate policy producing significant reduction in anthropogenic emissions of all greenhouse gases (GHGs) is implemented in the near future (starting around 2020), then a 2°C stabilization can be achieved without full decarbonization of human activity. However, if these GHG emissions continue to increase at the present pace throughout the middle of the century, then even an abrupt decrease of emissions to zero will not prevent surface temperature from exceeding 2°C threshold.

2. Methods

The MIT Integrated Global Systems Modeling (IGSM) consists of the Economic Projection and Policy Analysis (EPPA, Paltsev *et al.*, 2005; Chen *et al.*, 2016) model linked to the MIT Earth System Model (MESM, Sokolov *et al.*, 2005, 2009). The MESM is a climate-chemistry model of intermediate complexity, which couples a zonally-averaged model of atmospheric dynamics and chemistry, a thermodynamic sea-ice model, a land model with ecosystem biogeophysics and biogeochemistry, and a mixed layer/anomaly diffusing ocean model simulating heat and carbon uptake. The ocean carbon model includes the explicit parameterization of mixed layer biogeochemistry used in the MIT ocean GCM (Dutkiewicz *et al.*, 2005). The relation between diffusion coefficients for heat and carbon used in the simplified MESM model is based on the results of the simulations with the MIT ocean GCM (Dutkiewicz *et al.*, 2005; Sokolov *et al.*, 2007) and takes into account the carbon mixed down by the biological pump. The climate sensitivity and the rate of oceanic uptake of heat and carbon in the MESM, can be varied by changing the strength of the cloud feedback and the oceanic vertical diffusion coefficient (Sokolov, 2006). The MESM incorporates a fully coupled chemistry model, which simulates 33 species (Wang *et al.*, 1998) with 41 gas-phase and 12 heterogeneous reactions, with the chemistry in urban areas treated in reduced form sub-models (Mayer *et al.*, 2000). It simulates in detail, the terrestrial carbon cycle (Melillo *et al.*, 1993) and natural methane and nitrous oxide emissions (Prinn *et al.*, 1999). Some chemical species, including ozone, are simulated only in the troposphere. Prescribed stratospheric ozone is used in the radiation calculations. The MESM can be run in either concentration-driven or emission-driven modes.

The MESM was shown, with appropriate choice of climate sensitivity and the rate of ocean heat uptake, to reproduce global mean changes in surface air temperature (SAT) and sea level simulated by different AOGCMs (Sokolov *et al.*, 2003). The latitudinal pattern of changes in SAT is also very similar to those simulated by AOGCMs (Sokolov *et al.*, 2009). The MESM participated in a number of multi-model inter-comparison studies (e.g., Plattner *et al.*, 2008; Eby *et al.*, 2013; Zickfeld *et al.*, 2013; Olsen *et al.*, 2013, Brasseur *et al.*, 2015) showing in general comparable results to more complex models. For example, the study of the impact of aviation emissions on atmospheric chemical composition and climate showed that MESM results lie well within the envelope of the more complex 3-D chemistry-climate models (Olsen *et al.*, 2013).

As indicated above, in this study we are using a version of MESM with a simplified ocean sub-model (MESM2.2), which was also used in all the above-mentioned inter-comparisons, except Plattner *et al.* (2008). Sokolov *et al.* (2007) carried out a detailed comparison between MESM2.2 and MESM2.3 which incorporates the MIT ocean GCM (Dutkiewicz *et al.*, 2005). Their results showed that MESM2.2 matches the surface warming and changes in carbon cycle simulated by the MESM2.3 for runs over a few centuries under a range of emission scenarios.

In the simulations discussed below we use three sets of climate parameters for climate sensitivity (CS) of 2°C, 3°C and 4.5°C. Values for the rate of oceanic heat uptake (defined by the value of the effective vertical diffusion coefficient) and the strength of aerosol forcing **(Table 1)** are chosen to ensure consistency of MESM projected historical surface warming and changes in ocean heat content with available observations, based on the approach described in Forest *et al.* (2008). Aerosol forcing accounts for the radiative effects of different types of aerosols, primarily sulfate and black carbon. As mentioned above, the rate of carbon uptake by the ocean is linked to the rate of heat uptake. Values of the half-saturation constant, defining the CO_2 fertilization rate in the terrestrial ecosystem model (Melillo *et al.*, 1993; Prinn *et al.*, 1999, Felzer *et al.*, 2004), are chosen to make total carbon uptake in the beginning of the 21st century similar in all simulations.[1]

Table 1. Values of climate parameters used in simulations with the IGSM. LCR – low climate response, MCR – median climate response, HCR – high climate response.

	Climate sensitivity	Effective diffusion coefficient	Radiative forcing of aerosol–radiation interaction	Half-saturation constant for terrestrial carbon uptake[1]
	°C	*cm²/sec*	*W/m²*	*ppm*
LCR	2.0	0.5	-0.25	475
MCR	3.0	1.0	-0.53	425
HCR	4.5	1.5	-0.67	325

Table 2. Ranges of climate sensitivity (CS) and transient climate response (TCR): IGSM – for sets of climate parameters used in our simulation; AR5 - IPCC AR5 likely range; CMIP5 - 90% range from simulations with CMIP5 AOGCMs. AR5 values are from Stocker at al. (2013), and CMIP5 values from Table 9.5 of IPCC (2013).

IGSM		AR5		CMIP5	
CS	TCR	CS	TCR	CS	TCR
4.5	2.4	4.5	2.50	4.5	2.4
3.0	1.9	3.0	1.75	3.2	1.8
2.0	1.5	1.5	1.00	1.9	1.2

The range of climate sensitivity used in our simulations is slightly narrower than the IPCC AR5 likely range, but very similar to the range suggested by the CPMIP5 AOGCMs **(Table 2)**. While equilibrium surface warming for a given radiative forcing is defined by the climate sensitivity, transient changes are better described by the Transient Climate Response (TCR), which is defined as a change in surface air temperature at the time of CO_2 doubling in the simulations with 1%/year increase in CO_2 concentration. TCR for a given model is a function of both its climate sensitivity and its rate of oceanic heat uptake. Table 2 shows that the values of the TCR obtained in simulations for the combinations of climate sensitivity and rate of oceanic heat uptake reported in Table 1 agree well with IPCC and CMIP5 ranges. Values for the ratio of the TCR to climate sensitivity are 0.75, 0.63 and 0.53 for the LCR, MCR and HCR cases, respectively. For CMIP5 models this value ranges from 0.72 to 0.46 (excluding maximum and minimum values) with a mean value of 0.56 (Table

1 A larger half-saturation constant increases terrestrial C uptake for a given increase in CO_2 concentration.

9.5 in IPCC 2013). Historical (1861–2005) simulations with MESM showed that the use of a lower value of CS (e.g., 1.5°C) would require the use of a very low rate for oceanic heat uptake to produce surface warming consistent with available observations. This, however, would result in a very substantial underestimation of changes in ocean heat content. Based on those simulations, we chose 2°C as a lower limit for climate sensitivity.

Our choice of climate parameters ensures that the projected surface warming, both transient and at equilibrium, will fall into the IPCC *likely* interval. Values of the annual carbon uptake by the land and ocean fall into the IPCC ranges (**Tables 3 and 4**). The transient climate responses to cumulative carbon emissions (TCRE), defined as the ratio of surface warming to cumulative emissions at the time of CO_2 doubling from simulations with 1% per year increase in CO_2 concentrations, are 1.5, 1.8 and 2.2 K/EgC (Kelvin/Exagrams of Carbon) respectively for the LCR, MCR and HCR sets of climate parameters (Table 1). All these values fall in the upper half of the 5%-95% range, 0.8–2.4K/EgC, found in simulations with CMIP5 Earth system models (Gillett *et al.*, 2013).

Each climate simulation in this study consists of two parts: the concentration-driven simulation (from 1861 to 2005), in which the MESM model is forced by observed values of GHGs and aerosols, and the emission-driven simulation (from 2006 to 2500), where the model is forced by EPPA-derived and then extrapolated emissions of the various GHGs and aerosols. We denote simulations with the different sets of climate parameters (Table 1) as HCR (High Climate Response), MCR (Median Climate Response), and LCR (Low Climate Response).

Emissions projections to 2100 are produced by the EPPA model, which provides a multi-region, multi-sector recursive dynamic representation of the global economy. There are 18 geographical regions represented explicitly in the model, including ten major countries (USA, China, India, Brazil, Mexico, Japan, Canada, Russia, South Korea and Indonesia) and eight regional aggregations of other countries (European Union, Africa, Middle East, Dynamic Asia, Other Latin America, Australia&New Zealand&Oceania, Other Europe and Central Asia, Other East Asia).

The EPPA model includes representation of CO_2 and non-CO_2 (methane, CH_4; nitrous oxide, N_2O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; chlorofluorocarbons, CFCs, and sulfur hexafluoride, SF_6) GHG emissions abatement, and calculates reductions from gas-specific control measures as well as those occurring as a byproduct of actions directed at CO_2. The model also projects emissions of major air pollutants (sulfur oxides, SO_x; nitrogen oxides, NO_x; black carbon, BC; organic carbon, OC; carbon monoxide, CO; ammonia, NH_3; and non-methane volatile organic compounds, VOCs). These projections link these various emissions to the levels of activity in the energy, agriculture and other sectors that produce them.

Table 3. Ocean carbon uptake (GtC/year)

	1990–1999	2000–2009	2002–2011
MCR	2.05	2.40	2.51
HCR	2.27	2.66	2.78
IPCC AR5	2.2±0.7	2.3±0.7	2.4±0.7

Table 4. Land carbon uptake (GtC/year)

	1990–1999	2000–2009	2002–2011
LCR	1.02	1.94	2.12
MCR	1.03	1.51	1.90
HCR	0.96	1.44	1.73
IPCC AR5	1.1±0.9	1.5±0.9	1.6±0.9

Future scenarios are driven by economic growth (resulting from savings and investments) and by exogenously specified productivity improvement in labor, energy, and land. Demand for goods produced from each sector increases as GDP and income grow; stocks of limited resources (e.g., coal, oil and natural gas) deplete with use, driving production to higher cost grades; sectors that use renewable resources (e.g., land) compete for the available flow of services from them, generating rents. Combined with policy and other constraints, these drivers change the relative economics of different technologies over time and across scenarios, as advanced technologies only enter the market when they become cost-competitive.

The policy scenarios are constructed to reach certain cumulative emission targets that correspond to a particular temperature increase. They are designed in a similar fashion to those reported in US CCSP (2006), Prinn *et al.* (2011), and Paltsev *et al.* (2015a). The US CCSP exercise was the first comprehensive exercise that used radiative forcing stabilization levels and it served as a basis for the further development of the representative concentration pathway (RCP) scenarios by IPCC. In all scenarios considered here, the economic welfare is maximized. An advantage of our approach is that all scenarios are constructed with a set of consistent interactions between population growth, economic development, energy and land system changes and the resulting emissions of GHGs, aerosols, and air pollutants.

Contributions of different GHGs are quantified in terms of CO_2-equivalent emissions. These emissions are calculated using 100-year Global Warming Potentials (GWPs) from the IPCC Fifth Assessment (IPCC, 2013).

As a result, they allow estimation of expected warming by the end of the century and are used as a target in the simulations with the EPPA model. We follow the Hyman *et al.* (2002) methodology to estimate the abatement cost curves for non-CO_2 gases in all sectors of the economy. In the scenarios considered here we impose emission permit trading between CO_2 and other GHGs (CH_4, N_2O, PFCs, HFCs, SF_6) based on their GWPs. The model chooses the abatement quantities of GHGs that equate the cost of reduction of different GHGs in different sectors. The emission profiles, constructed in such a way, are the result of an assumed global economy-wide policy with the GHG constraints consistent with cumulative emissions required to limit the average surface air temperature increases in 2100 at a designated level above pre-industrial.

Anthropogenic emission profiles for CO_2, CH_4 and N_2O for all three scenarios are provided in **Figure 1**, where emissions for the RCP2.6 scenario (van Vuuren *et al.*, 2011) are also shown for comparison. As shown in Figure 1(a), anthropogenic CO_2 emissions (fossil-fuels, industrial and land-use change related) in our scenarios are reduced from about 9.5 GtC/year in 2020 to about 2.6–7 GtC/year (30–70% reduction) by 2050 and then to 1–2.8 GtC/year (70–90% reduction) by 2100. Natural CH_4 and N_2O emissions in 2006 are about 140 $TgCH_4$/year and 10 TgN/year, respectively. Thus, total CH_4 and N2O emissions in our simulations are close to the estimates given by Kirschke *et al.* (2013) and Huang *et al.* (2008).

Depending on assumed values of parameters defining magnitude of climate system response to radiative forcing and strength of carbon cycle, CO_2-equivalent total anthropogenic GHG emissions should decrease by about 55–75% by the end of the century to limit surface warming by 2°C above pre-industrial (**Figure 2**).

We extend the emission profiles from 2100 to 2500 to keep the surface air temperature near the 2°C above preindustial target for this remaining interval of the simulation. These post-2100 emissions of most GHGs and air pollutants are assumed to decline at their average annual rates of decline between 2090 and 2100. For example, CO_2 emissions decrease after 2100 at the rate of about 1.5%/year in all scenarios. For those emissions that decline slower than 0.7% per year in the HCR and LCR projections, and slower than 0.4% per year in the MCR projection, the rates of decline were increased correspondingly through 2200. After 2200, minimal rates of decline in the emissions are set to 0.1% per year in all cases. While we take into account temperature driven increases in natural CH_4 and N_2O emissions, CO_2 and CH_4 emissions associated with possible permafrost thawing are not considered. According to Schneider von Deimling *et al.* (2015), the impact of these emissions in

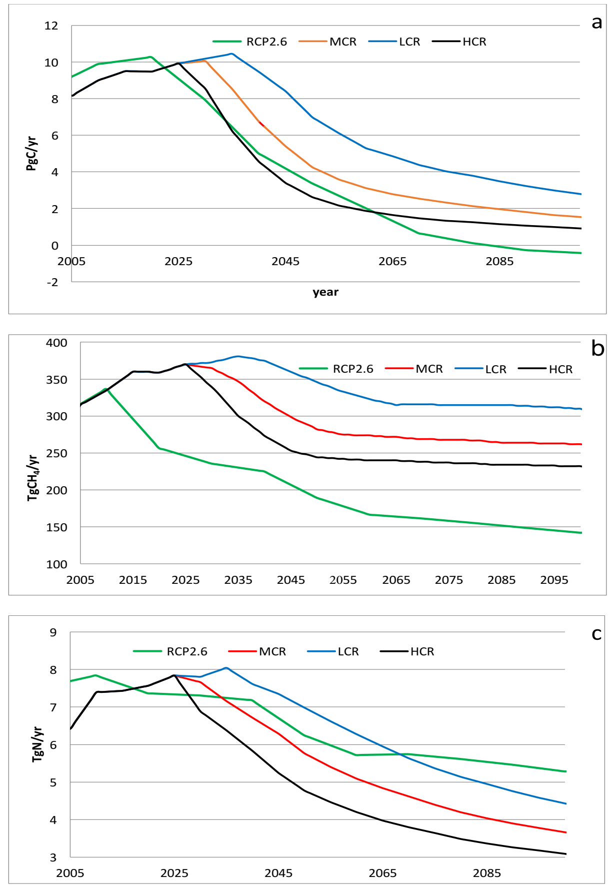

Figure 1. Annual emissions for LCR, MCR and HCR case and for RCP2.6 of (a) CO_2, (b) CH_4 and (c) N_2O

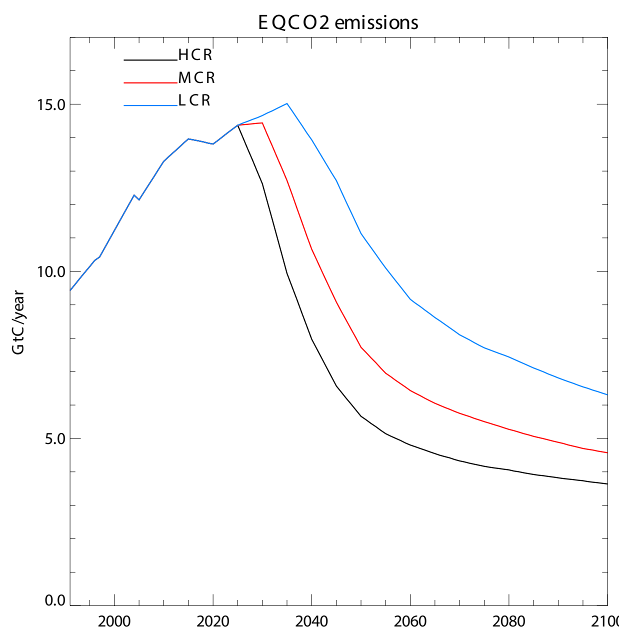

Figure 2. Annual CO_2 equivalent emissions in GtC/year using 100-year GWPs.

the RCP2.6 scenario (which is close to our policy scenarios) is rather small. An apparent feature of the 2°C climate target is that it requires an extremely aggressive emissions reduction at a global level starting in the very near future.

3. Results and Discussion

3.1 Emissions and Climate

Due to the large share of CO_2 in total emissions and because it stays in the atmosphere for a very long time (e.g., Matthews and Caldeira, 2008: Zickfeld *et al.*, 2013), changes in radiative forcing and surface temperature are, to a large extent, defined by changes in CO_2 concentrations. Atmospheric CO_2 concentrations, in their turn, depend on the balance between anthropogenic carbon emissions and carbon uptake by the ocean and terrestrial ecosystems.

Figure 3 shows the total net anthropogenic carbon emissions and uptakes for the duration of the simulations. As noted above, during the historical stage of the simulations, MESM is forced by prescribed GHG concentrations. CO_2 concentrations simulated in the second stage of the simulations are defined not only by CO_2 emissions but also by industrial emissions of CH_4 and CO (that produce CO_2 with ~month to ~decade time delay). For this reason, the implied carbon emissions are shown in Figure 3. Emissions and uptake peak at about 11 GtC/year and 5 GtC/year, respectively, resulting in a maximum in

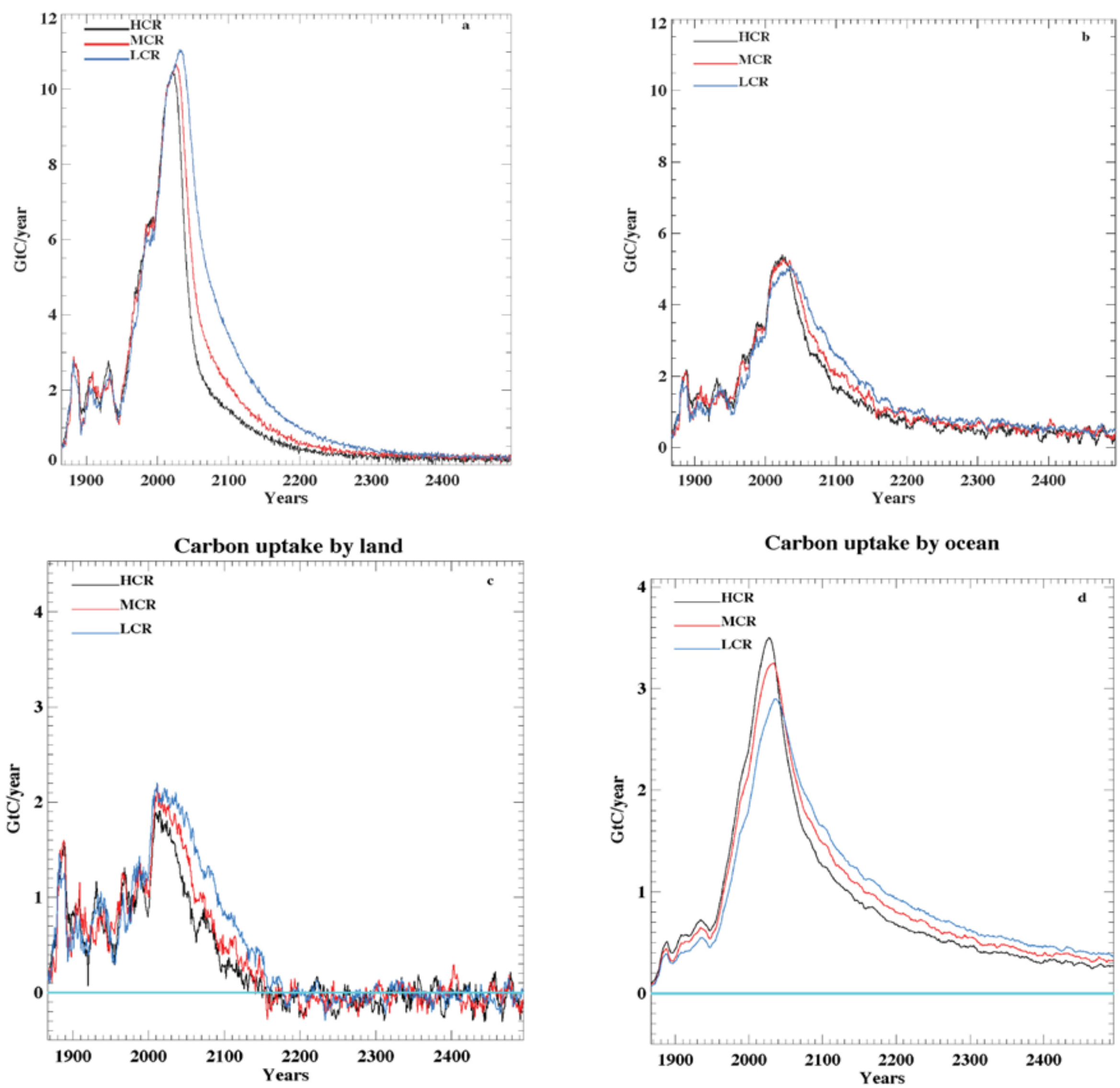

Figure 3. (a) Total net anthropogenic carbon emissions , and (b) total (land +ocean), (c) land and (d) ocean carbon uptakes. All units are GtC/year.

the net atmospheric carbon flux of 5–6 GtC/year (Figure 3). There is a noticeable difference between changes in emissions and uptake, determined primarily by the rates of emission changes and the rates of carbon mixing from the mixed layer into the deep ocean.

In all simulations, after peaking the total carbon uptake decreases slower than the net anthropogenic emissions, especially in the HCR simulation due to the higher rate of carbon mixing from the mixed layer into the deep ocean. As a result, in the HCR simulation the difference between the net anthropogenic carbon emissions and the total land plus ocean uptake becomes negative around 2050 (**Figure 4**). In the other two simulations (MCR, LCR), this difference crosses the zero line at around 2100 and 2200 respectively. As expected, the terrestrial ecosystem comes into equilibrium with atmospheric CO_2 much faster than the ocean. Carbon uptake by land (Figure 3c) becomes zero around 2150 in all simulations, while the ocean (Figure 3d) still absorbs about 0.5 GtC/year in 2500.

Changes in the net anthropogenic emissions minus the land plus ocean uptake determine the changes in CO_2 concentrations (**Figure 5**). In the HCR simulation, CO_2 concentrations increase through 2050 rising from about 400 ppm in 2015 to about 450 ppm at 2050 and then decrease to about 420 ppm in 2500. In the MCR and LCR simulations, they are rising through 2100 and 2240 and, peaking at about 480 ppm and 550 ppm, respectively. By 2500, concentrations have slightly decreased to 455 ppm in the MCR case and 530 ppm in the LCR case. As was noted in a number of publications (e.g. Matthews and Caldeira, 2008: Zickfeld *et al.*, 2013), CO_2 stays in the atmosphere for a very long time. Figure 5 shows that despite the drastic reduction in net anthropogenic carbon emissions, CO_2 concentrations fall only by 4–7% of total CO_2 from their peak values.

The CO_2-equivalent concentrations, shown in **Figure 6**, are calculated from the total radiative forcing relative to 1860[2]. The CO_2-equivalent concentrations shown here account for radiative forcing by all GHGs and aerosols (sulfates, BC). The difference in CO_2-equivalent concentrations during the historical phase (1861–2005) in our

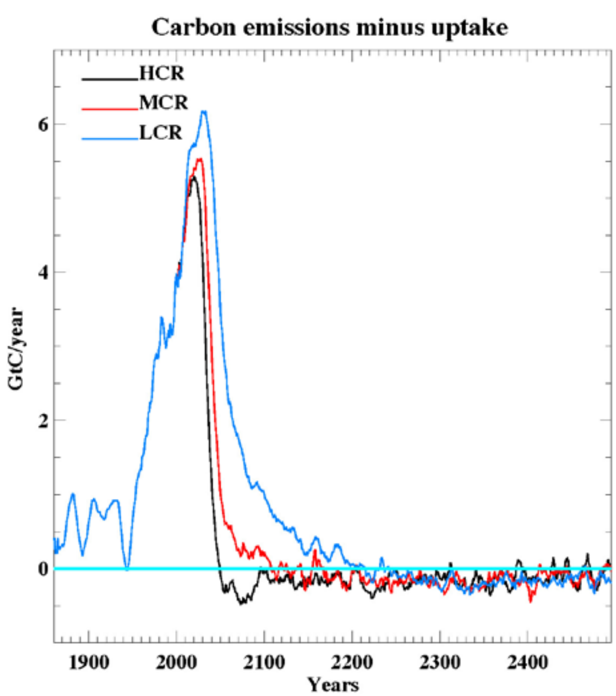

Figure 4. Difference (GtC/year) between net anthropogenic carbon emissions and total land plus ocean uptake. Light blue horizontal line indicates zero difference.

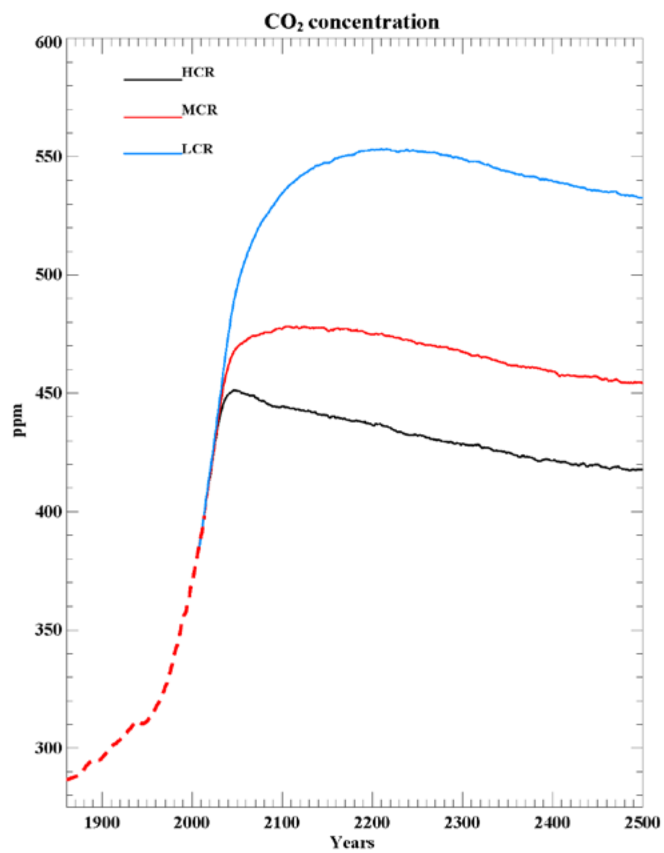

Figure 5. Atmospheric CO_2 concentrations (mole fractions in ppm CO_2). Dashed red line shows observed values used in historical part of simulations.

2 It should be noted, that there is no connection between CO_2 equivalent emissions (that use the GWP approximation) shown in Figure 2, and the CO_2 equivalent concentrations shown in Figure 6 (see Pierrehumbert,, 2014 for more details) . The use of CO_2 equivalent concentrations simply provides another way to compare CO_2 and non- CO_2 radiative forcing.

three simulations is due to different assumptions about the strength of aerosol radiative forcing in the HCR, MCR, and LCR scenarios. The CO_2-equivalent concentrations calculated from radiative forcing due to GHGs only are identical in all simulations until 2015 and agree well with those calculated from GHG observations. Total radiative forcing (**Figure 7**) and thus CO_2-equivalent concentrations start to decrease earlier and faster than CO_2 concentrations because of a more rapid decrease in abundant short-lived GHGs (CH_4, O_3, etc.) as well as sulfates and black carbon).

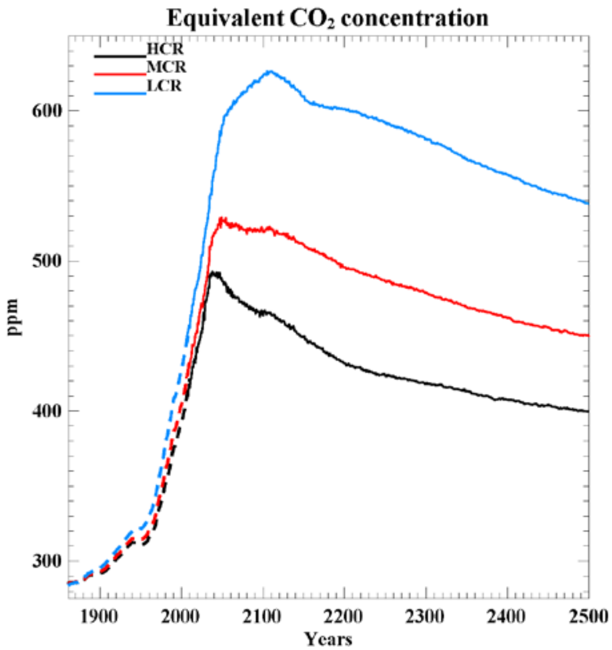

Figure 6. Atmospheric CO_2-equivalent concentrations (mole fractions in ppm CO_2-eq) computed from radiative forcing by all GHGs and aerosols. Dashed lines for historical part and solid lines for future part of each simulation.

The only GHGs that decrease much slower than CO_2 are CF_4 and SF_6, but their associated forcing is extremely small. This sharp decrease in non-CO_2 forcing more than offsets a sharp decrease in the cooling effect of sulfate aerosol even in the HCR case where negative sulfate aerosol forcing for a given sulfate loading is largest (Table 1).

The CO_2-equivalent concentrations are rising from levels of about 430–475 ppm in 2015 to about 490, 530, and 625 ppm in 2045, 2050 and 2100, respectively, in the HCR, MCR, and LCR cases. They start to decline slowly after their peak values, and by 2500 the CO_2-equivalent concentrations are about 400 ppm in the HCR case, 450 ppm in the MCR case, and 540 ppm in the LCR case.

Methane and tropospheric ozone concentrations decrease below their 1860 values by the end of the 22nd, 24th and 25th centuries in the HCR, MCR and LCR cases, respectively. As a result, their radiative forcing relative to 1860 becomes negative, which explains why the CO_2-equivalent concentrations become lower than the CO_2 concentrations in the MCR and HCR cases.

The resulting changes in the annual mean surface air temperature relative to a mean of 1861–1880 are presented in **Figure 8**. For all three cases, surface temperature stabilizes at about 2°C after 2100. Recall that, while all three cases require very sharp emissions reductions, none of them require zero anthropogenic carbon emissions in 2050 or

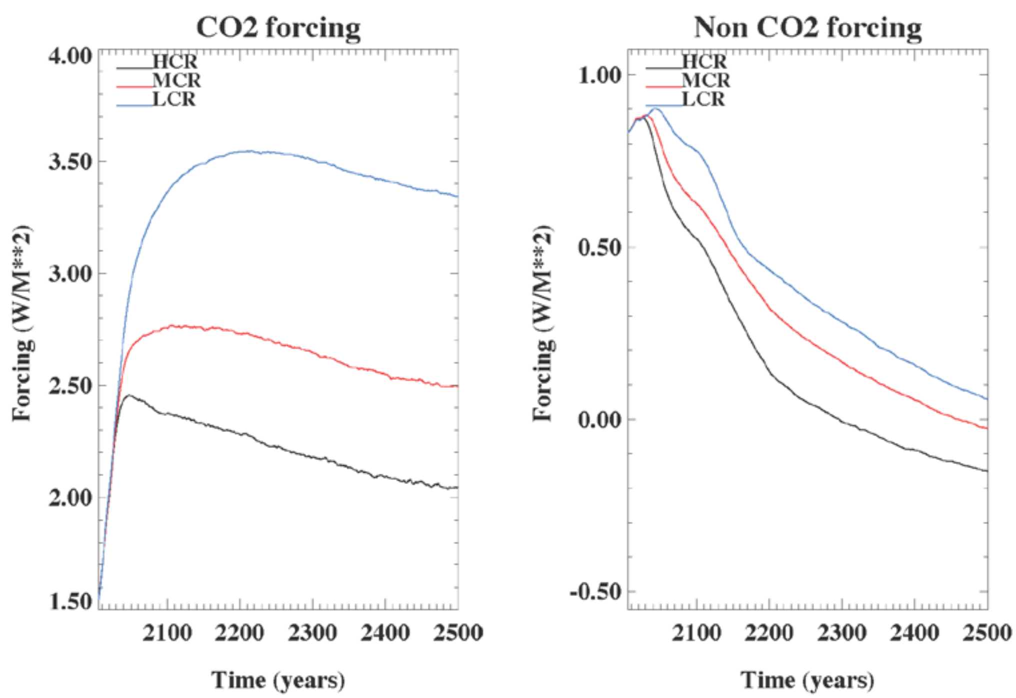

Figure 7. Radiative forcing due to CO_2 and non-CO_2 GHGs.

even 2100. It should, however, be kept in mind that the decreases in CO_2 emissions in our three scenarios are accompanied by sharp declines in the emissions of all other GHGs. The nearly constant temperatures after 2100 are a result of compensation between the decrease in radiative forcing and the already committed warming due to the thermal inertia of the ocean.

According to the IPCC (2014), to limit human-induced warming to less than 2°C with a probability of 66%, the cumulative carbon emissions (from CO_2, CH_4 and CO) should be around 700–860 GtC. From 1870 to 2011, the world has emitted about 515 GtC, which leaves about 180–340 GtC to be emitted for the 2°C climate stabilization goal. Those estimates are based on the hypothesis of a near-linear relationship between SAT and cumulative carbon emissions. The dashed lines in **Figure 9** show the results from three simulations with a no-policy emission scenario for the same three sets of climate parameters. With no policy, the relationship between cumulative carbon emissions and surface warming is very similar to the one shown in Figure SPM 5b of IPCC (2014). However, in our three policy simulations this linearity breaks down around 2100, the shape of the cumulative carbon vs. temperature line changes, and the surface air temperature stays near 2°C above preindustrial in spite of the continued increase in cumulative carbon emissions.

The total amount of carbon emitted from 2011 to 2100 is 400, 500 and 650GtC in the HCR, MCR and LCR cases, respectively. Rogelj *et al.* (2015b), who also considered non-CO_2 mitigation, estimated in their reference case that cumulative carbon emission of 340 and 460GtC from 2011 to 2100 would allow 2°C stabilization with probabilities of 66% and 50% respectively, in the case with stringent CH_4 mitigation (following RCP2.6) these values increases to 435 and 560GtC.

To estimate probabilities of SAT increase by the end of the 21st century we ran ensembles of simulations for each of our three scenarios using the online version of MAGICC6 model (Meinshausen *et al.*, 2011). As can be seen from **Table 5**, the probabilities for SAT increases being less then 2°C at 2100 are about 25%, 50% and 75% for the emission scenarios used in the LCR, MCR and HCR cases, respectively.

Table 5. Percentiles of SAT change at 2100 from 600-member ensembles with MAGICC6.

	17%	25%	50%	75%	83%
LCR	1.92	2.02	2.28	2.58	2.71
MCR	1.68	1.76	1.99	2.26	2.38
HCR	1.51	1.58	1.78	2.03	2.15

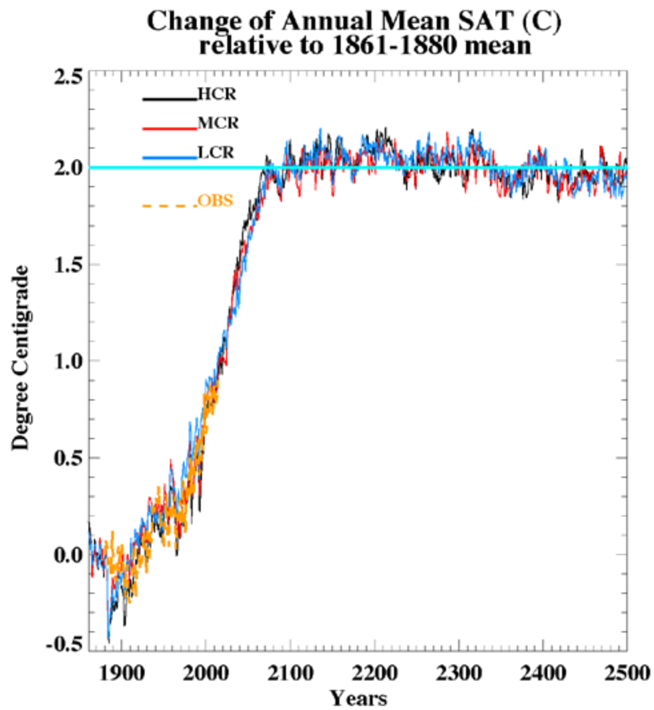

Figure 8. Change over time in the global average surface air temperature relative to the 1861–1880 mean. Light blue horizontal line indicates the 2°C target.

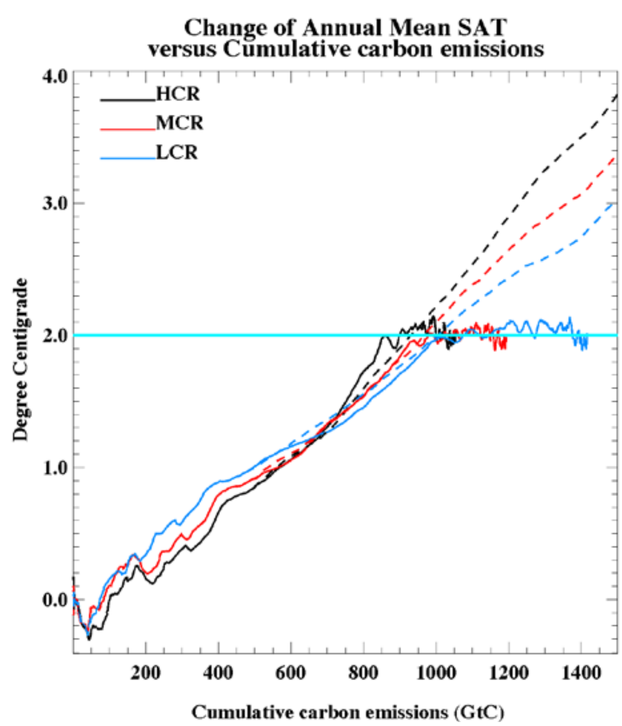

Figure 9. Relationship between the cumulative net anthropogenic carbon emissions and global average surface air temperature increase. Solid lines refer to the three policy cases. Dashed lines show results from simulations with no policy. Light blue horizontal line indicates 2°C target.

The fact that the surface temperature stays almost constant after 2100 is to a large extent explained by the fact that aggressive emissions reduction policies for all GHGs were applied very early in the 21st century (starting in 2020). Because of that early start, the rate of increase in radiative forcing is significantly reduced or even reversed by 2100, and the resulting global heat imbalance is rather small. As a result, the subsequent decrease in forcing, associated with the decrease in non-CO_2 emissions and the fact that carbon emissions are decreasing faster than total carbon uptake, prevents surface temperature from rising and leads to the relationship shown in Figure 9 between cumulative carbon emission and SAT. It should be noted that results for no policy simulations (dashed lines) are shown to 2100 only, while the three policy cases were run through 2500 (solid lines). Note also that the cumulative carbon emissions over the last four centuries of our simulations are rather small, namely 150, 210 and 310 GtC in the HCR, MCR and LCR cases, respectively.

If the implementation of our climate policies is delayed until SAT reaches the 2°C threshold, then warming will continue for some time even if all anthropogenic emissions are cut to zero, and the relationship between emissions and temperature will be different from that shown above. To demonstrate this, we carried out a number of additional simulations. The first two were similar to the MCR simulation but with either CO_2 emissions or all anthropogenic emissions (GHGs and aerosols) set to zero after 2100. The second pair of simulations was done using the MCR climate parameters and no policy emissions scenario until the global SAT reached 2°C above preindustrial (at year 2054), at which time again either CO_2 or all subsequent emissions (GHGs plus aerosols) were also set to zero. Temperature changes in the no policy simulations with zero CO_2 emissions after 2054 are similar to those in simulations discussed by Frölicher and Paynter (2015), namely global SAT continues to increase through 2500 (**Figure 10**). Even if we eliminate all anthropogenic emissions, global SAT increases for a few years before starting to fall. In the simulations with MCR emissions, global SAT starts to decrease right after 2100 in both additional simulations, but much faster if all emissions are set to zero.

The relationships between cumulative carbon emissions and SAT changes for simulations with zero CO_2 emissions (**Figure 11**) show that the equilibrium climate response to emissions (CRE) (Frölicher and Paynter, 2015) can be larger or smaller than the transient CRE depending on the preceding emission and temperature trajectories.

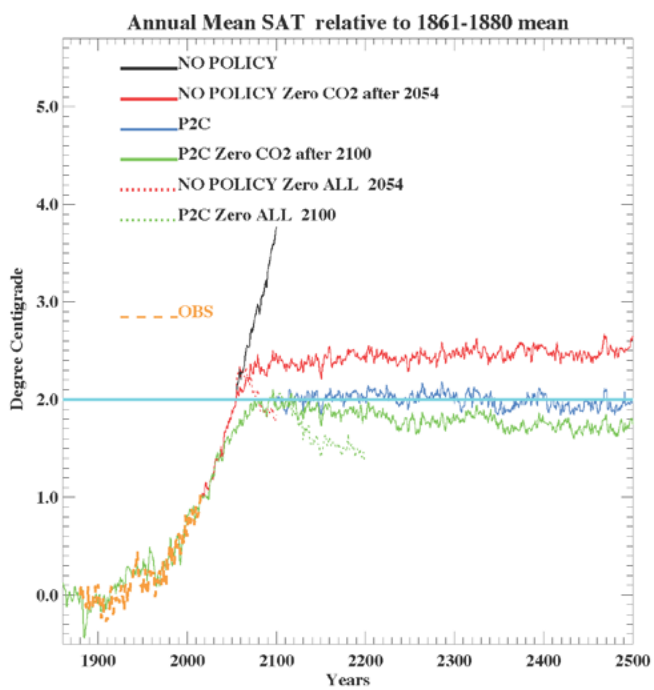

Figure 10. Change over time in the global average surface air temperature (SAT) relative to the 1861–1880 mean in simulations with no policy till 2100 (black line), with no policy till 2054 and zero CO_2 emissions after that (red line), 2°C policy (blue line) and 2°C policy till 2100 and zero CO_2 emissions after that (green line). Results from simulations with all anthropogenic emissions (GHGs plus aerosols) set to zero are shown by dotted red and green lines.

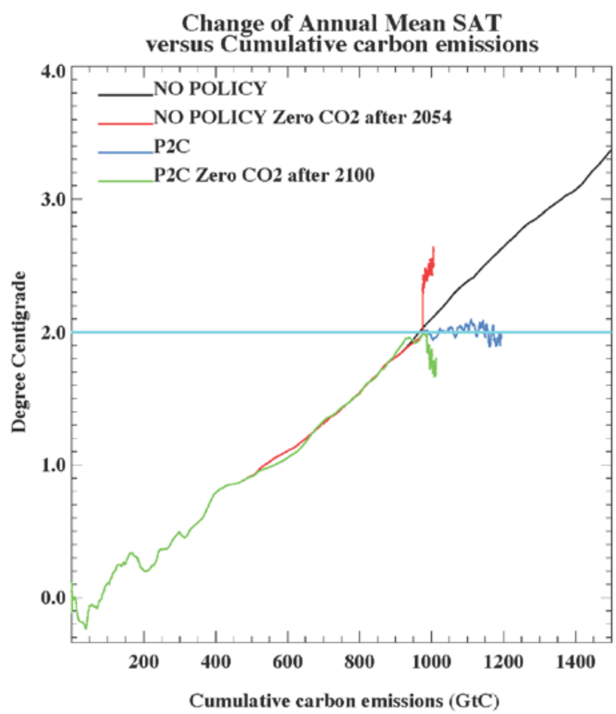

Figure 11. Relationship between the cumulative net anthropogenic carbon emissions and global average surface air temperature for MCR in simulations with no policy until 2100 (black line), with no policy until 2054 and zero CO_2 emissions after that (red line), 2°C policy (blue line) and 2°C policy until 2100 and zero CO_2 emissions after that (green line). The small increase in cumulative carbon emissions in the two simulations with zero CO_2 emissions is caused by non-zero anthropogenic emissions of CH_4 and CO.

Whether SAT will continue to rise or will start to decrease after CO_2 emissions are cut to zero depends, among other factors, on the magnitude of the earth's energy imbalance at the time of emissions cutoff. This imbalance can be estimated by the difference of simulated SAT at this point and an equilibrium SAT corresponding to the radiative forcing. In the no policy simulation, forcing is increasing though 2054 and equilibrium SAT corresponding to 2054 forcing is significantly higher (3.4°C) than 2°C. In simulations with MCR emissions, forcing starts to decrease 50 years before CO_2 emissions were set to zero, and two temperatures are much closer, namely 2.6°C and 2°C. In this case, a decrease in forcing overcomes the SAT increase caused by the inertia of the climate system ("climate commitment"). Simulated SAT changes under zero CO_2 emissions also depend on the values of model parameters and the resulting ratio of TCR to climate sensitivity. To demonstrate this, we carried out two additional simulations with no policy before 2054 and zero CO_2 emissions after 2054 using the model parameters from the HCR and LCR cases. For the LCR parameters, the ratio of TCR to climate sensitivity is rather large and SAT does not increase after 2054 (**Figure 12**). In contrast, for the HCR setting, SAT increases noticeably faster than for the MCR setting.

3.2 Implications for Technology Mixes & Costs

The technology mixes and costs to achieve the 2°C target are highly dependent on the assumptions about the future costs of low-carbon and zero-carbon technologies. In all three of our cases, the global energy system requires substantial transformations in a relatively short time. With currently held assumptions about the cost trajectories for the needed advanced technologies, the 2°C stabilization incurs a world GDP reduction (relative to our no climate policy) of 5–10% in 2050 and 15–20% in 2100. Changes in the structures of national economies, electrification of energy use in industrial sectors, and lower costs of advanced technologies may reduce these numbers.

As for the technology mix, **Figure 13** shows a sensitivity of such calculations to the prevailing views about the cost of low-carbon technologies. Figure 13(a) represents the IGSM calculations using the estimates for carbon capture and storage (CCS) technology costs that were based on the MIT Future of Coal study (2007) and used for the U.S. Climate Change Science Program Report (US CCSP, 2007). Subsequent industrial experience with CCS showed that these initial cost estimates of the technology were quite optimistic. Figure 13 (b) shows an alternative

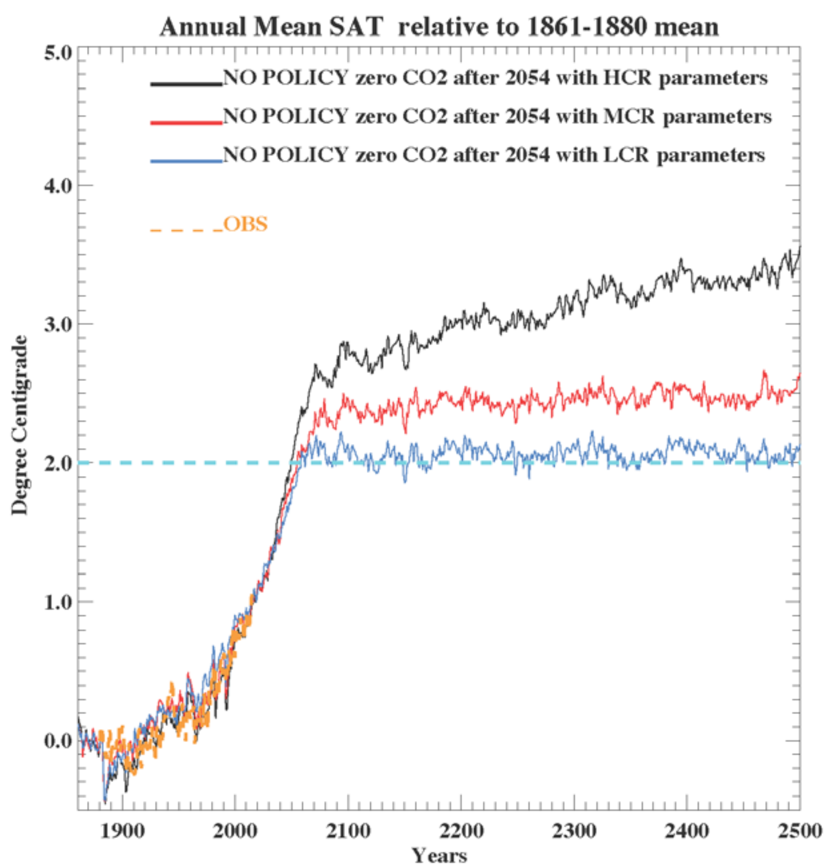

Figure 12. Change over time in the global average surface air temperature relative to the 1861–1880 mean in simulations with no policy till 2054 and zero CO_2 emissions after that for HCR (black line), MCR (red line), and LCR (blue line) model parameters.

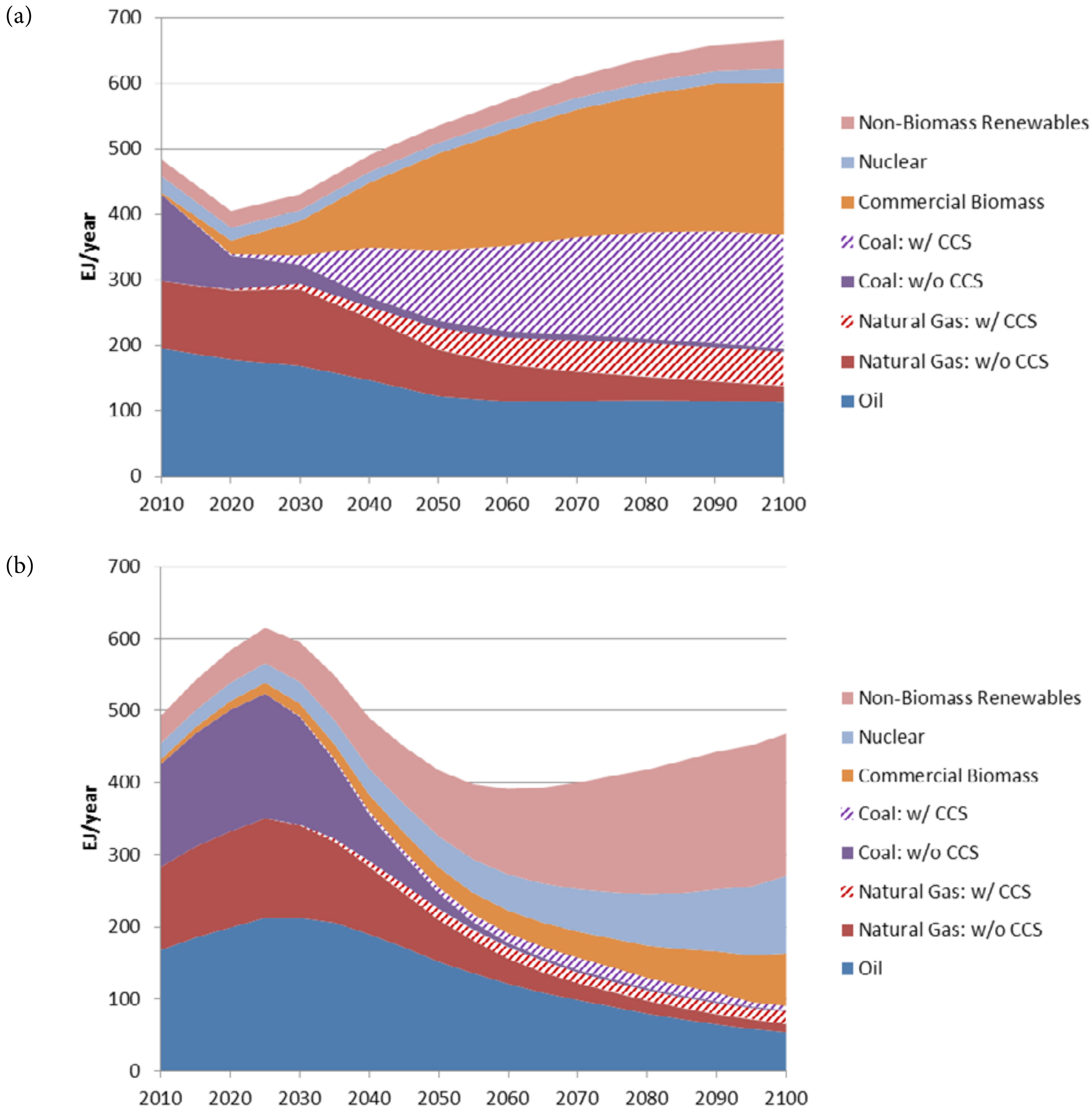

Figure 13. Change in total global energy use (in exajoules/year) by type, as estimated by the EPPA model for the MCR case: (a) Optimistic view on carbon capture and storage; (b) Optimistic view on renewables and energy efficiency.

view on the technology mix required for the 2°C target. In comparison to the 2007 Future of Coal study, we see a reduced role of CCS and biomass, and an increased role of renewables (wind and solar), nuclear (mostly in the regions outside of US and Europe) and energy efficiency (that drives a reduction in energy use). It should be emphasized that in both of these views, cost estimates (and viability of the needed very large deployment rates) are uncertain. The successful deployment of several large-scale projects in different situations and locations will be important to assess whether any assumed costs can actually be realized.

While the exact mix of technologies is subject to substantial uncertainty (which argues for targeting emission reduction from any affordable source rather betting on certain kinds of low-carbon energy sources), in all three of our cases the energy system required drastic changes, both short and long term. Because one might be easily (and almost certainly) wrong in picking the winning technologies, economists have long argued that carbon pricing (or carbon taxes) is the best way to ensure such an energy transformation at the lowest possible cost for society (Rausch and Karplus, 2014; Paltsev *et al.*, 2015b).

4. Conclusions

In international climate policy discussions, there is currently a call for "net zero" anthropogenic emissions by 2100, or even by 2050, where the "net" emissions are defined as anthropogenic emissions minus anthropogenic sinks such as re-forestation and biomass electric power with carbon capture and storage. Our analysis of the 2°C stabilization scenarios with the MIT IGSM framework shows, in agreement with a number of previous publications (e.g. Allen *et al.*, 2009; Matthews *et al.*, 2009, 2012; Zickfeld *et al.*, 2009), that surface air temperature can be kept near 2°C above preindustrial without net anthropogenic carbon emissions being reduced to zero by either 2050 nor 2100. Reducing global net anthropogenic CO_2 emissions to about 2.6–7 GtC/year by 2050 and then to about 1–2.8 GtC/year by 2100 is still consistent with the 2°C stabilization goal. For our calculated rates of CO_2 emission decrease, the oceans and terrestrial ecosystems absorb enough carbon (together with aggressive reduction in other anthropogenic emissions) to prevent GHG concentrations, radiative forcing, and surface temperature from exceeding the desired thresholds. A major reason for our results is that the land and ocean uptake rates are a function of the total atmospheric CO_2 concentration and, due to the very long lifetime of CO_2, this does not decrease anywhere near as fast as the imposed CO_2 emissions.

While our calculated net anthropogenic emissions minus natural ocean and terrestrial sinks, are close to zero around 2100, global anthropogenic emissions fall below 1 GtC only by 2200 under the median climate response (MCR) assumptions. Ultimately, net anthropogenic emissions should approach zero for climate stabilization, but our results indicate that that need not happen by 2050 or even 2100. Our model specifically includes all major climate radiative forcing agents (GHGs and aerosols, and we show that an aggressive mitigation of non-CO_2 emissions allows for a slower decrease in CO_2 emissions than are required in simulations with models including only CO_2.

Our study indicates that there appear to be technologically feasible emissions scenarios which would allow the change in global average temperature to remain below 2°C from pre-industrial, although these scenarios would require a rapid change in global energy systems that would likely cause a significant reduction in global GDP. With mitigation focused on all forcing agents, it may also be possible to achieve this objective without resorting to net zero carbon emissions by 2050 or even 2100, but this is uncertain, and longer term emissions would still likely have to be very small or zero. Our study assumes that emission reduction starts in 2020. Delaying implementation of strict climate policy until even 2030 will significantly affect the magnitudes and costs of the required reductions of both CO_2 and non-CO_2 emissions (e.g. Sanderson *et al.*, 2016).

Long-term stabilization of the temperature near 2°C above preindustrial levels also depends on the emissions profiles after 2100. Our simulations assume that during 2100 to 2500 CO_2 emissions continue to decrease at the same rate (1.5%/year) as in the 2090–2099 decade, and that CH_4 and CO emissions decrease by 0.4–0.7%/year during 2100–2099 and by 0.1–0.2%/year after 2200. With these trajectories of anthropogenic emissions, surface air temperature stays nearly constant despite the continued (though very slow) increase in cumulative anthropogenic carbon emissions. Such a dependency between cumulative carbon emissions and SAT is possible only because radiative forcing in our IGSM simulations was decreasing substantially for most of the 21st century. The uncertainty about the future costs of the needed new technologies provides an indication that the best way to achieve the required energy transformation is to include emission reductions from any feasible source rather than focusing on specific kinds of low-carbon energy. Although emissions need to be reduced to zero eventually to achieve climate stabilization, the results of our simulations suggest that net anthropogenic emissions do not have to be zero by 2050 or 2100 to meet the 2°C target because of the natural carbon sinks in oceans and terrestrial ecosystems and the inclusion of reductions in short-lived forcers (O_3, BC, CH_4).

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