The carbon-climate system response at high amounts of cumulative carbon emissions, and the role of non-CO_2 forcing and observational constraints on cumulative carbon budgets

by

Katarzyna B. Tokarska

BSc, Simon Fraser University, 2012
MSc, Simon Fraser University, 2014

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Supervisory Committee

Dr Nathan P. Gillett (Co-Supervisor)
(Canadian Centre for Climate Modelling and Analysis,
School of Earth and Ocean Sciences, University of Victoria)

Dr Andrew J. Weaver (Co-Supervisor)
(School of Earth and Ocean Sciences, University of Victoria)

Dr Vivek K. Arora (Departmental Member)
(Canadian Centre for Climate Modelling and Analysis,
School of Earth and Ocean Sciences, University of Victoria)

Dr David E. Atkinson (Outside Member)
(Department of Geography, University of Victoria)

Abstract

The long-term global mean temperature depends on the total amount of anthropogenic CO_2 emitted. This direct link between temperature and cumulative CO_2 emissions has implications for policymakers, as the cumulative emissions framework identifies the total amount of carbon that can be emitted, referred to as a cumulative carbon budget, that is consistent with reaching stabilization of the global mean temperature at desired levels, such as 1.5 °C or 2.0 °C warming above the pre-industrial level. This dissertation is a compilation of three studies that explore the relationship between warming and cumulative carbon emissions at high amounts of total carbon emitted (Project I; Chapter 2), its sensitivity to non-CO_2 forcing (Project II; Chapter 3), and constraining the climate model responses with observations, in order to provide more accurate estimates of the carbon budget consistent with 1.5 °C warming above the pre-industrial level (Project III; Chapter 4). A joint summary of the key findings from each project, and their significance, is presented in Chapter 5.

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List of Acronyms

CE	Cumulative carbon emissions (defined in Section §3.3.2)
CEB	Carbon budget, or cumulative emissions budget (defined in Section §3.3.2)
CMIP5	Fifth Phase of the Coupled Model Intercomparison Project
CO_2	Carbon dioxide
ECS	Equilibrium Climate Sensitivity
EgC	Trillion tonnes of carbon, equivalent to 1000 GtC or 1000 PgC
EMIC	Earth System Model of Intermediate Complexity
ESM	Earth System Model
GCM	General Circulation Model
GtC	Giga-tonnes of carbon, equivalent to 1 PgC
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Fifth Assessment Report from the Intergovernmental Panel on Climate Change
IPCC SMP	Intergovernmental Panel on Climate Change: Summary for Policymakers
PgC	Petagrams of Carbon, equivalent to 1GtC
RCP	Representative Concentration Pathway
TAB	Threshold avoidance (carbon) budget
TCRE	Transient climate response to cumulative emissions
TEB	Threshold exceedance (carbon) budget
UNFCC	United Nations Framework Convention on Climate Change

Acknowledgements

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

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To my loving parents, who unceasingly
encourage me to keep pursuing my dreams

Chapter 1. Introduction

The long-term global mean temperature depends on the total amount of anthropogenic CO_2 emitted (IPCC AR5: Collins et al., 2013). Recent studies have shown that the increase in the global mean temperature is proportional to the total amount of anthropogenic CO_2 emitted (Matthews et al. 2009; Allen et al., 2009; Zickfeld et al., 2009; Gillett et al., 2013; IPCC AR5: Collins et al., 2013). This direct link between temperature and cumulative CO_2 emissions has implications for policymakers, as the cumulative emissions framework identifies the total allowable CO_2 emissions that are consistent with reaching stabilization of the CO_2-induced global mean temperature response at desired levels, such as 1.5°C or 2°C warming above the pre-industrial temperature (Gillett et al., 2013; IPCC AR5: Collins et al., 2013; Friedlingstein et al., 2014a).

The total amount of anthropogenic carbon that can be emitted in a multi-gas emission scenario, in order not to exceed a given threshold of the global mean temperature, is referred to as the *threshold avoidance carbon budget* (Rogelj et al., 2016; further defined in Section 1.4), or simply a *carbon budget* consistent with a given level of warming, as referred to in this dissertation.

This dissertation explores the relationship between warming and cumulative carbon emissions at high amounts of total carbon emitted (Project I, Chapter 2), its sensitivity to non-CO_2 forcing (Project II, Chapter 3), as well as providing an explanation of the differences between the CO_2-only and multi-forcing carbon budgets reported by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5, 2013) (Project II, Chapter 3). It also attempts to constrain the climate model responses with observations, in order to provide more accurate estimates of the carbon budget consistent with 1.5°C warming above the pre-industrial level (Project III, Chapter 4). The specific research questions for each of the three projects are then explicitly stated at the beginning of each chapter.

The following three sections in this chapter (Section 1.1- Section 1.4) serve as background information about the relationship between warming and cumulative carbon emissions, and provide a brief review of the current literature relevant to this topic.

1.1. Transient Climate Response to Cumulative Emissions (TCRE)

The ratio of temperature change to total carbon emissions is defined as the transient climate response to cumulative emissions (TCRE, Gillett et al., 2013) or the climate-carbon cycle response (CCR, Matthews et al., 2009). The TCRE measure incorporates both the carbon cycle response to emissions and the physical climate response to elevated CO_2 levels (Gillett et al., 2013), thereby aggregating the carbon cycle and climate feedbacks into a single measure (Matthews et al., 2009).

Figure 1 shows the progression from CO_2 emissions to climate change (Matthews et al., 2009). The first progression from CO_2 emissions to atmospheric CO_2 concentrations is subject to carbon sensitivity, determined by the strength of natural carbon sinks. Subsequently, the second progression from CO_2 concentrations to climate change is subject to climate sensitivity (and depends on the sensitivity of temperature response to CO_2 concentrations) (Matthews et al., 2009).

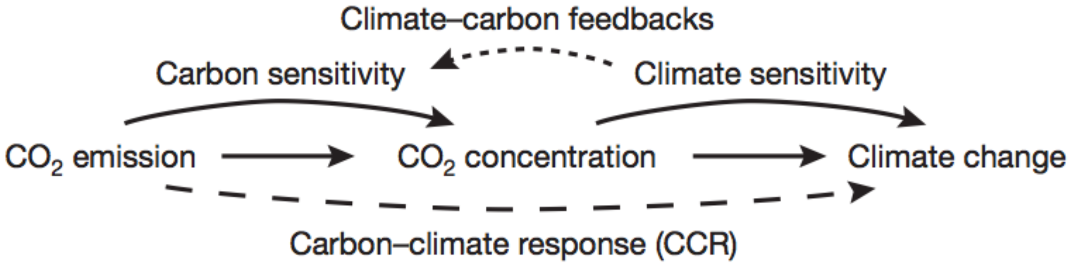

Figure 1. Schematic representation of the progression from CO_2 emissions to climate change. Source: Matthews et al., (2009). Note: Carbon-climate response (CCR) is equivalent to the Transient Climate System Response to Cumulative Carbon Emissions (TCRE).

TCRE aggregates the uncertainties related to climate-carbon feedbacks, carbon sensitivity and climate sensitivity into a single metric that directly relates the change in temperature and CO_2 emissions (Figure 1), providing a robust metric for inter-comparison of output from different climate models (Matthews et al., 2009). TCRE combines the physical and biogeochemical responses of the climate system to CO_2 emissions scenarios (Zickfeld et al., 2012) and is approximately linear and independent of the time and emissions scenario (Matthews et al., 2009; Gillett et al., 2013; Zickfeld et al., 2013).

Equilibrium Climate Sensitivity

The global mean temperature at which the climate system stabilizes (reaches an equilibrium state) under a scenario of doubling of the atmospheric CO_2 concentration is defined as equilibrium climate sensitivity (ECS; IPCC, 2007). The best estimate for the value of the climate sensitivity is 3˚C, and its value is likely (probability > 66%) in the range 1.5-4.5˚C (IPCC AR5: Collins et al., 2013).

1.2. TCRE linearity and its limits

Both carbon cycle responses and physical climate system responses exhibit a nonlinear behaviour due to multiple feedbacks present in the climate system (Friedlingstein et al., 2014a, Arora et al., 2013, Zickfeld et al., 2011). Yet, the relationship between CO_2-induced warming and cumulative carbon dioxide emissions is known to remain approximately linear up to two trillion tonnes of carbon emitted (Matthews et al. 2009; Allen et al., 2009; Zickfeld et al., 2009; Collins et al, 2013; Gillett et al., 2013; Zickfeld et al., 2013). This linearity arises from a near-cancellation of different effects: the saturation of the natural carbon sinks as the atmospheric CO_2 concentration continues to increase, the approximately logarithmic relationship between atmospheric CO_2 concentrations and radiative forcing (Matthews et al., 2009; MacDougall, 2016), and a decline in the rate of the ocean heat uptake efficiency at higher levels of warming (Gregory et al., 2015; Rogelj, 2016).

This approximate linearity of TCRE response is known to hold for cumulative CO_2 emissions below 2000 PgC and until temperatures peak (Matthews et al., 2009; Zickfeld et al., 2012; Gillett et al., 2013; IPCC AR5, 2013; Friedlingstein et al., 2014a; MacDougall, and Friedlingstein, 2015). Matthews et al. (2009) noted that TCRE is likely to decrease for cumulative emissions above 2000 PgC.

A previous study of Allen et al., (2009), using a simple climate model, also suggested that TCRE may decline beyond 2000 PgC. Similarly, Herrington and Zickfeld (2014) explored TCRE for cumulative CO_2 emissions up to 5275 PgC for an Earth System Model of intermediate complexity (UVic ESM). In that case, TCRE is found to decrease for higher cumulative emissions targets beyond 2000 PgC. However, these previous results for high cumulative emissions are based primarily on EMICs, and further research is needed to explore TCRE behaviour for higher amounts of cumulative carbon emissions. We address this gap in current literature in Project I (Chapter 2), by exploring TCRE at higher amounts of cumulative carbon emissions in Earth system models, beyond two trillion tonnes of carbon emitted.

1.3. TCRE and non-CO_2 forcing

The transient climate response to cumulative emissions (TCRE), as described in Section 1.1 was calculated for the CMIP5 models by Gillett et al., 2013 from 1PCTCO2 increase simulations, where the atmospheric CO_2 concentration increases at a rate of 1% per year until doubling of the preindustrial atmospheric CO_2 level (Figure 2). Therefore, the carbon budgets derived directly from this framework are based on CO_2 emissions only and do not consider impacts of non-CO_2 greenhouse gases.

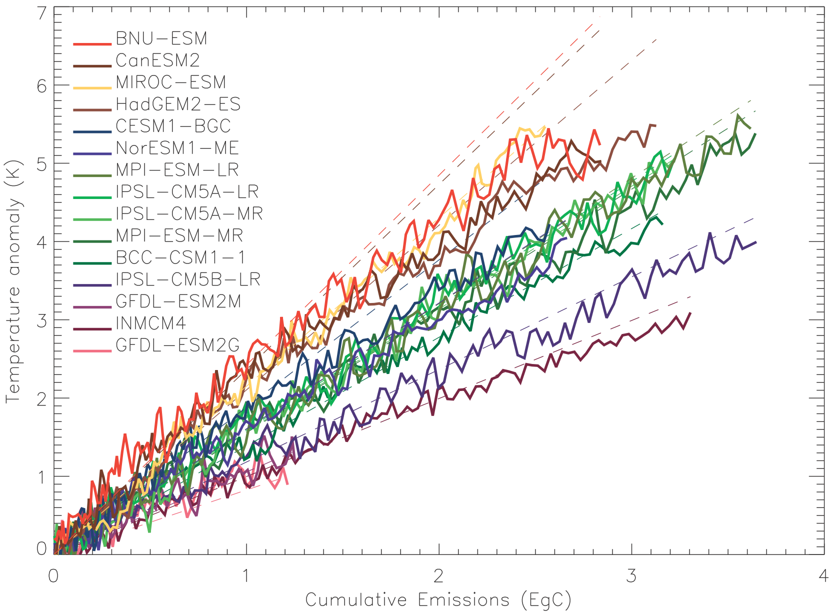

Figure 2. Temperature as a function of cumulative CO_2 emissions for 1PCTCO2 simulations, modelled by 15 CMIP5 models. Source: Gillett et al., 2013.

Recent studies have examined the role of non-CO_2 forcing in reducing carbon budgets that would be consistent with different levels of warming, as the non-CO_2 forcing contributes additional warming under all scenarios studied, and this additional warming could also affect the natural carbon sinks (Gillett and Matthews, 2010; MacDougall and Knutti, 2016). However, these studies are based on climate models of intermediate complexity. Project II (Chapter 3) addresses this gap in the current research by looking at the impacts of non-CO_2 forcing on cumulative carbon budgets and carbon cycle feedbacks using a comprehensive Earth system model.

1.4. TCRE and the Paris Agreement

Paris Agreement goals

At the United Nations Climate Change Conference in Paris (COP 21) in November 2015, 195 countries adopted the Paris Agreement that commits ratifying countries to:

> *"Holding the increase in the global average temperature to well below 2 ºC above pre-industrial levels, and pursuing efforts to limit the temperature increase to 1.5 ºC above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (UNFCC, 2015; Article 2).*

As a result of actions arising from the Paris Agreement, COP 21 invited the IPCC to 'provide a special report on the impacts of global warming of 1.5°C above preindustrial levels, and related global greenhouse gas emission pathways', and IPCC has accepted the invitation to provide such report in year 2018.

Threshold avoidance vs. exceedance carbon budgets

Cumulative carbon emission budgets can be classified as threshold exceedance budgets (TEB) (IPCC AR5: Collins et al., 2013, Rogelj, et al., 2016), if they are based on scenarios, which, by design, exceed the given warming threshold. In contrast, threshold avoidance budgets (TAB) (IPCC AR5: Collins et al., 2013; Rogelj, et al., 2016) are based on emission pathways that never exceed the given threshold warming level. Carbon budgets derived from RCP simulations considered here can be classified then as the threshold exceedance budgets (TEB), since they exceed the warming thresholds of 1.5 ºC and 2.0 ºC, which are the key focus of Chapter 4 of this dissertation.

1.5. Structure of this dissertation

This dissertation explores the transient climate system response to cumulative carbon emissions (TCRE) and cumulative carbon budgets under different conditions, as specified in the following three areas of research:

- Project I: Assessing the linearity of the relationship between warming and cumulative carbon emissions at high amounts of cumulative carbon emissions (Chapter 2).
- Project II: Understanding the influence of non-CO_2 forcings on cumulative emission budgets reported by the IPCC (Chapter 3).
- Project III: Observationally constraining cumulative carbon budgets consistent with 1.5 °C warming (Chapter 4).

Each of these three research areas is explained in more depth in the subsequent Chapters 2, 3, and 4, respectively. Each chapter contains motivation, specific research questions, methods and preliminary results that are relevant for each project. The general conclusions are reported in Chapter 5.

Chapter 2. Project I: Assessing the linearity of the relationship between warming and cumulative carbon emissions at high amounts of cumulative carbon emissions

This chapter is based on the contents of the paper:

K.B. Tokarska, N.P. Gillett, A.J. Weaver, V.K. Arora, and M. Eby. (2016). The climate response to five trillion tonnes of carbon. *Nature Climate Change*, 6, 851–855.
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2.1. Introduction and motivation

If no further climate mitigation actions are pursued on a global scale, and the Earth's remaining fossil fuel resources continue to be combusted under a business-as-usual scenario, the resulting total amount of carbon emitted could be as high as five trillion tonnes of carbon (5 EgC), corresponding to the lower bound of the fossil fuel resources estimate (IPCC, 2013; Resources to Reserves, 2013; Swart and Weaver, 2012). The question arises what would be the resulting warming incurred by the Earth under such business-as usual scenario and what would be the ultimate magnitude of climate change in the absence of further mitigation actions.

The relationship between warming and total amount of carbon emitted has been shown to be approximately linear for '*cumulative emissions up to about 2000 PgC until the time that temperatures peak*' (IPCC 2013, Summary for Policymakers, p.17; explained more in Section §1.2). However, it is not clear if this linear relationship continues for higher amounts of carbon emitted. A few previous studies, using simpler climate models, suggest that the ratio of warming to cumulative emissions may decline for higher amounts of cumulative carbon emitted (Allen et al., 2009, Herrington and Zickfeld, 2014).

2.2. Research Questions

The key research questions that we focus on this project are:

- Does the relationship between warming and cumulative carbon emissions continue to be approximately linear even for higher amounts of total carbon emitted (up to 5 trillion tonnes of carbon)?
- How much would the Earth warm under a no-mitigation scenario resulting in cumulative carbon emissions of 5 trillion tonnes of carbon (equivalent to the lower bound of the fossil fuel resource estimate)?
- How do the climate model responses under such high-emission scenario differ between comprehensive Earth system models (ESMs) and Earth system models of intermediate complexity (EMICs), and what processes could be responsible for those differences?

2.3. Methods

2.3.1. Models and scenarios

This project makes use of the Representative Concentration Pathway Extension (RCP 8.5-Ext) scenario, which is a no-mitigation scenario of continually increasing prescribed greenhouse gas concentrations (Figure 3). The effective radiative forcing reaches 8.5 W/m^2 in year 2100 and stabilizes at 12 W/m^2 in year 2300 (Meinshausen et al., 2011). The analysis is based on four comprehensive Earth system models (ESMs) from the Fifth Coupled Climate Model Intercomparison Project (CMIP5; Taylor et al., 2012), driven by the RCP 8.5-Ext scenario. Although the RCP 8.5-Ext simulations extend well outside the range of conditions for which the models' parameterizations could be validated against reality, these parameterizations are based on physical, chemical and biological principles, and sampling over multiple models accounts, in part, for uncertainties associated with differences in the representation of physical climate system and carbon cycle between models (Arora et al., 2013; Friedlingstein et al., 2014b).

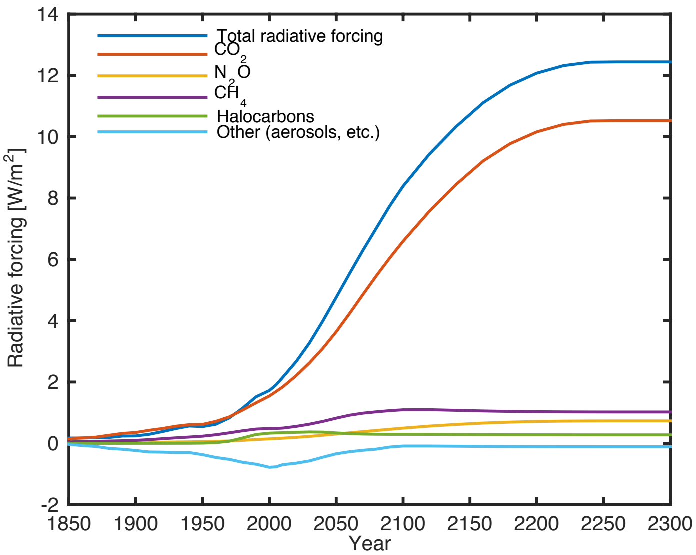


Figure 3. Radiative forcing prescribed for the RCP 8.5 Extension pathway. Note: scenarios are based on the Representative Concentration Pathways database (van Vuuren et al., 2011; Meinshausen et al., 2011).

In further parts of the analysis, responses from 1PCTCO2 simulations are also used, in which the atmospheric CO_2 concentration increases at a rate of 1% per year for 140 years, starting from the pre-industrial value of approximately 285 ppm, and all other forcings stay at their pre-industrial levels (Gillett et al., 2010; Figure 2).

In addition to CMIP5 model responses, which are the primary focus of this study, responses from seven Earth system models of intermediate complexity (EMICs; Eby et al., 2013; Zickfeld et al., 2013) are also analysed, in order to compare the climate system responses under the high-emission scenario for those two classes of climate models (ESMs and EMICs).

Although estimates of fossil fuel reserves and resources are highly uncertain, and the amount used under a business as usual scenario would depend on prevailing economic and technological conditions, an amount of five trillion tonnes of carbon (5 EgC), corresponding to the lower end of the range of estimates of the total fossil fuel resource (IEA, 2013), is often cited as an estimate of total cumulative emissions in the absence of global mitigation actions, under a business-as-usual scenario.

The cumulative carbon emissions were calculated by time-integration of the atmosphere-land and atmosphere-ocean carbon fluxes (or by adding the land carbon reservoirs, if the atmosphere-land carbon flux data was not available for some models). (The method of calculating cumulative carbon emissions is explained in detail in Section 3.3.2 of the following chapter). The warming and precipitation at 5 EgC (representing the lower bound of fossil fuel resource estimate in the absence of further mitigation; Swart and Weaver, 2010; IEA 2013) were calculated for each model at the year when its cumulative carbon emissions reach 5 EgC ±10 years.

2.3.2. CO_2-attributable warming

The RCP8.5-Ext simulations are not driven exclusively by changes in CO_2 concentration, but also include changes in other greenhouse gases and aerosols. The non-CO_2 forcing (such as methane, nitrous oxide, halocarbons and aerosols; Figure 3) is approximately constant during the period 2100-2300 and CO_2 is the dominant forcing in the RCP 8.5-Ext scenario: the ratio of CO_2 to total radiative forcing is 79% in 2100 and 85% in 2300 (Figure 3). Therefore, the CO_2-attributable warming was calculated by scaling the temperature response from the RCP 8.5 Ext simulation that includes all radiative forcings (both CO_2 and non-CO_2) by the ratio of CO_2 radiative forcing to total radiative forcing, respectively for each year.

Particularly in the period after 2100, which is the primary focus of this paper, this is likely a good approximation, since the ratio of CO_2 to total forcing is approximately constant over this period, so differences in the time profile of forcing and response are not important, and aerosol and ozone forcing are close to zero over this period. Hence, the ratio of CO_2 to total forcing is determined by the radiative forcings of the well-mixed greenhouse gases which are well constrained and not strongly model-dependent (Figure 3).

The assumptions about components of radiative forcings in RCP pathways are based on different combinations of economic, technological, demographic, policy, and institutional future scenarios (van Vuuren et al., 2011). In the long run, beyond year 2100, non-CO_2 greenhouse gases remain approximately constant in the future RCP pathways, to account for their approximately constant emission rates and short lifetimes, compared to a much longer lifetime of CO_2 forcing. For example, sustained higher methane emissions would increase the non-CO_2 component of the warming. However, CO_2 is the dominant component of radiative forcing on the time-scales considered here (beyond year 2100).

2.4. Results

2.4.1. Climate change under no-mitigation scenario

Global mean temperature

The four CMIP5 models simulate global mean surface temperature increases of between 8.1 and 11.5 °C for the period 2281-2300 relative to 1986-2005 in the RCP 8.5-Ext scenario (Figure 4 a). These increases are towards the upper end of the 4.9–10.7 °C (5-95% confidence interval; IPCC AR5 Table 12.2) range given for the full ensemble of CMIP5 models which carried out these simulations (Colins et al., 2013), and generally higher than increases of between 3.8 and 8.9 °C simulated by seven Earth system models of intermediate complexity (EMICs) in 2300 (Figure 4 gray lines). (Individual EMIC temperature responses are shown in Figure 6, for comparison).

Carbon fluxes

The fluxes of carbon into both land and ocean exhibit progressive increases in all models until the mid-21st century, followed by a gradual decline in the atmosphere-land and atmosphere-ocean fluxes during the 2100-2300 period, despite the continuously increasing atmospheric CO_2 concentrations (Figure 4 panels b and c, respectively), consistent with previous findings (Zickfeld et al., 2013; Randerson et al., 2015).

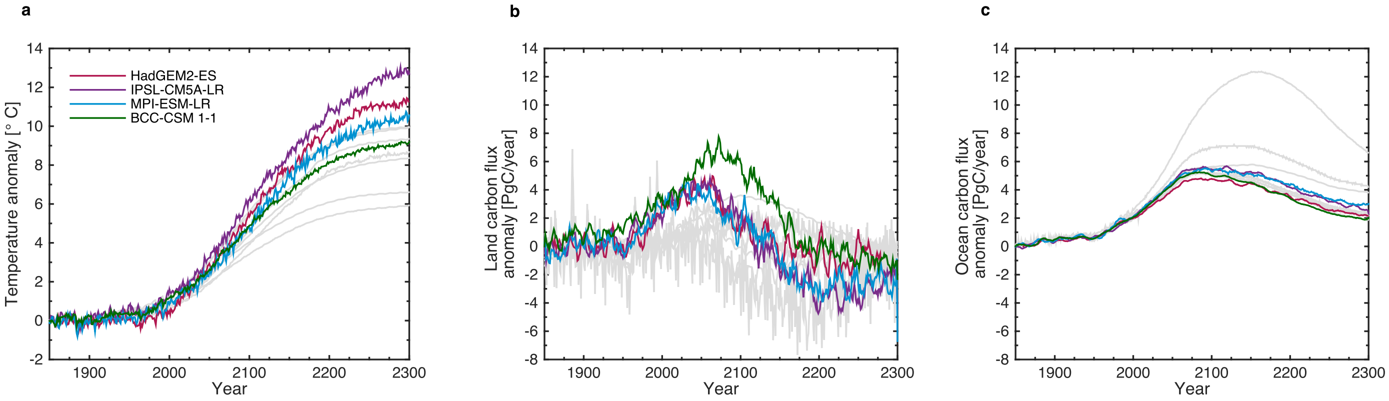


Figure 4. Global mean temperature and carbon fluxes simulated in the RCP 8.5-Ext simulations. Global mean near-surface temperature anomaly (a), atmosphere-land carbon flux anomaly (b), atmosphere-ocean carbon flux anomaly (c). Anomalies are calculated with respect to the corresponding year in the pre-industrial control simulation to remove the effects of any drift. The carbon fluxes (panels b and c) are 10-year running means. Grey lines indicate EMIC responses for comparison, based on Zickfeld et al., 2013.

Cumulative carbon emissions

Cumulative CO_2 emissions, derived from the sum of changes in atmospheric CO_2 burden and time-integrated atmosphere-land and atmosphere-ocean carbon fluxes (Collins et al., 2013), are shown in Figure 5 d (and Figure 6 b for EMICs) (The method of calculating cumulative carbon emissions is explained in detail in Section 3.3.2 of the following chapter). Total cumulative emissions increase strongly up to 2200, followed by approximate stabilization around 5 EgC by 2300 (Figure 5 d), in response to stabilization of atmospheric CO_2 concentration (Figure 5 c).

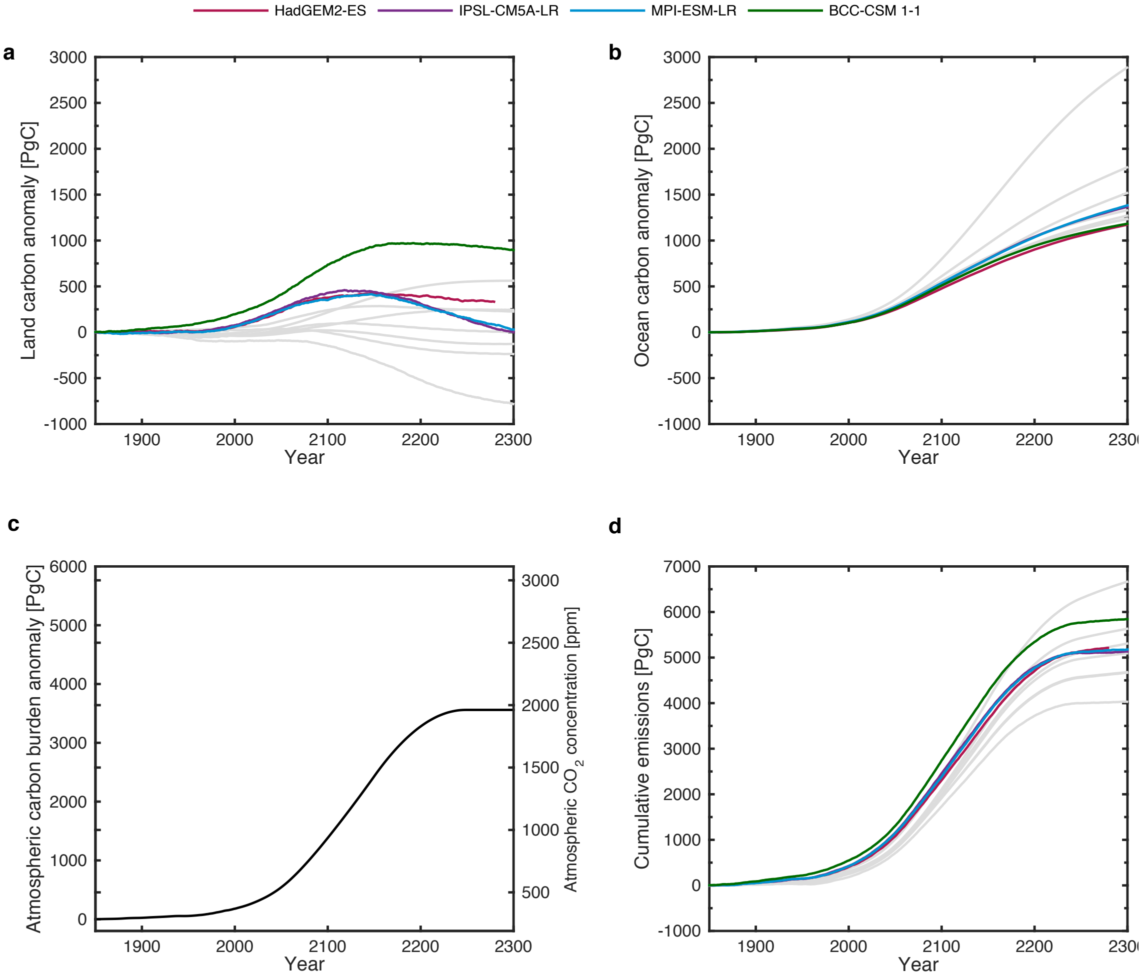


Figure 5. Carbon budget quantities. Panels (a) and (b) show cumulative atmosphere-land and atmosphere-ocean CO_2 fluxes for the period 1850-2300, after taking into account any drift in the pre-industrial control simulation. Panel (c) shows changes in prescribed atmospheric carbon burden for the historical (1850-2005), RCP 8.5 (2006-2100) and RCP 8.5-ext (2101-2300) scenarios. Panel (d), which is a sum of panels (a), (b) and (c), shows the diagnosed cumulative CO_2 emissions consistent with the prescribed CO_2 pathway in panel (c) as simulated by the four ESMs. Anomalies are calculated with respect to the corresponding year in the pre-industrial control simulation to remove the effects of any drift. Grey lines indicate EMIC responses for comparison.

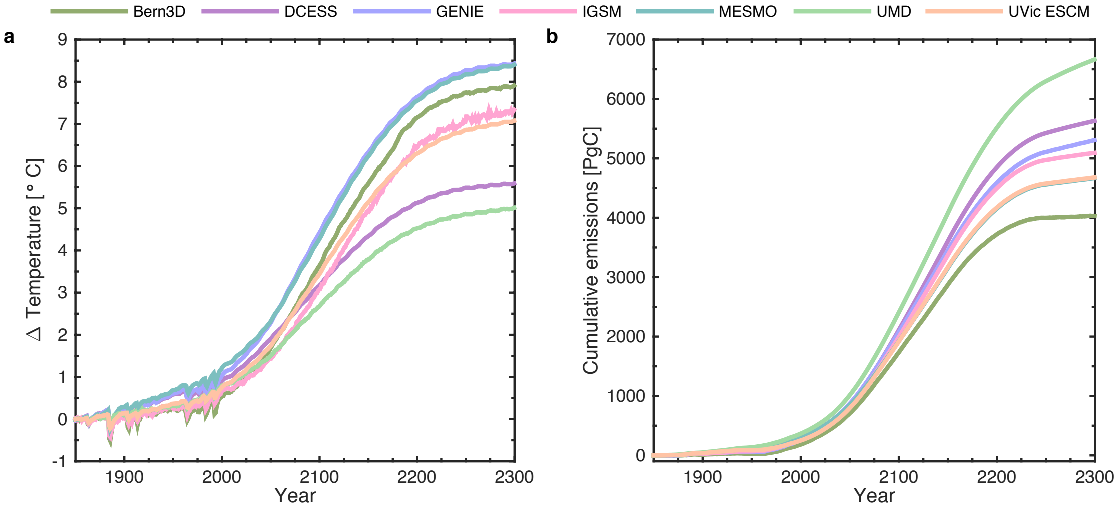


Figure 6. Earth system models of intermediate complexity: Global mean temperature (a) and cumulative carbon emissions (b). Anomalies are relative to 1850-1860 mean. The EMIC data is based on Zickfeld et al., 2013.

Land carbon uptake

Time-integrated carbon fluxes, representing the atmospheric, land and ocean carbon reservoir evolution over time, are shown in Figure 5. The land continues to take up carbon until year 2100 due to the CO_2 fertilization effect at high CO_2 concentration (Figure 5a). Subsequently, a decline in terrestrial carbon storage occurs during the period 2100-2300 for MPI-ESM-LR and IPSL-CM5A-LR, most likely due to an increase in heterotrophic respiration more than that in net primary productivity, as the CO_2 fertilization effect saturates at higher CO_2 levels and higher temperature levels limit photosynthesis, especially in tropical regions (Figure 7b) (Eby et al., 2013; Zickfeld et al., 2013; Arora et al., 2014). In MPI-ESM-LR and IPSL-SM5A-LR total land carbon is close to preindustrial levels in 2300 despite the CO_2 concentration of 1677 ppm, owing to pronounced carbon-climate feedbacks (Arora et al., 2013). The land carbon pool stabilizes but does not decline for HadGEM2-ES and BCC-CSM 1.1. The land carbon uptake would be expected to be weaker if the models included nutrient constraints on photosynthesis (Friedlingstein et al., 2014b; MacDougall et al., 2012), or some representation of down-regulation of photosynthesis with increasing CO_2 (Arora et al., 2009). Models considered here show an increase in carbon uptake in the boreal zone (Figure 7) due to increased vegetation growth in those regions at higher temperatures. However, if the boreal vegetation does not increase much with warming, the net terrestrial carbon uptake would be further reduced, and dominated by the outgassing of the land carbon sink in the Tropics (Figure 7). Overall, the spread in the land carbon uptake across the models arises from different representation of the terrestrial carbon uptake processes and feedbacks (such as the strength of the CO_2-fertilization effects, and photosynthesis temperature to mortality representation), which are highly uncertain between models (Friedlingstein et al., 2014b; Arora et al., 2013). The uncertainties in the land and ocean carbon uptake are comparable when judged across the ensemble of ESMs and EMICs (Figure 5). However, by the end of the 21st century, ocean carbon uptake (Figure 5b) is substantially larger than the land carbon uptake, therefore, the results presented here would not be much influenced by the uncertainties related to the representation of the terrestrial carbon cycle processes.

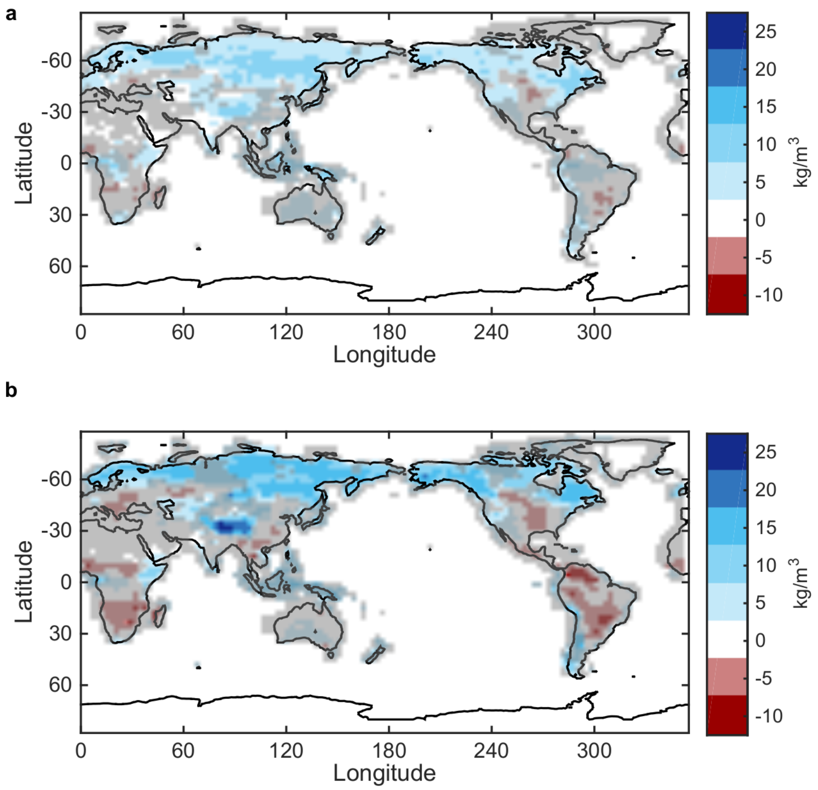


Figure 7. Simulated multi-model mean changes in the land carbon pool (a) for the period 2090-2110 and (b) at the time of 5 EgC emissions. Anomalies are shown relative to the preindustrial control simulation. The grey shaded areas indicate regions of inconsistent model responses, where at least one model shows change in the opposite direction to the multi-model mean.

Ocean carbon uptake

For all the models, the ocean continues to take up carbon to the year 2300, albeit at a decreasing rate of uptake than after 2100 (Figure 5 b). While there are significant differences in the regional pattern of land carbon uptake response, the regions of highest carbon uptake in year 2100 generally occur in the northern high latitudes, while much of the tropics release carbon to the atmosphere (Figure 7). The regional responses intensify at 5 EgC of carbon released, compared to 2100 (Figure 5 b), indicating even more outgassing in the tropics due to unfavourably high temperatures negatively affecting vegetation growth and more uptake in the northern high latitudes, likely driven by more vegetation growth due to warmer temperatures in that region.

2.4.2. Warming and cumulative carbon emissions

TCRE at 5 EgC

Figure 8 shows the relationship between temperature change and cumulative carbon emissions for the four CMIP5 Earth system models (Figure 8 a) and the seven EMICs considered (Figure 8 c). In order to approximate the response to CO_2 changes alone, temperature changes in Figure 8 a and Figure 8 c were scaled by the ratio of CO_2 radiative forcing to total radiative forcing, respectively for each year (as explained in Section §2.3.2).

Figure 8a and Figure 8c also compare RCP 8.5-Ext simulations with 1PCTCO2 simulations, in which CO_2 increases at a rate of 1% per year, and all other forcings stay at their pre-industrial levels (1PCTCO2, Figure 8, dotted lines, based on Gillett et al., 2013). Note that the sharp increase in temperature as a function of cumulative emissions at the end of the IPSL-CM5A-LR and MPI-ESM-LR simulations in Figure 8, results from ongoing warming (Figure 4a) during a period in which cumulative emissions are approximately constant (Figure 5d), a feature previously seen in some other models (Allen et al., 2009; Frölicher & Paynter, 2015). Figure 8a shows that the warming in the RCP 8.5-Ext simulations scaled by the ratio of CO_2 to total forcing, for a given magnitude of cumulative emissions, is slightly higher than for 1PCTCO2 experiments. One possible reason for this is the warming from non-CO_2 greenhouse gases, which reduces the diagnosed cumulative emissions in the RCP 8.5-Ext simulations (Collins et al., 2013) associated with the carbon-climate feedback. Nonetheless, Figure 8a suggests that the ratio of warming to cumulative emissions continues to behave approximately linearly even up to cumulative emissions of 5 EgC. This result was verified by estimating the global warming due to CO_2 only at 5 EgC emissions for each of the four ESMs which ran the full RCP 8.5-Ext simulations (Section 2.3.2). This warming was used to calculate the ratio of CO_2-attributable warming to emissions at 5 EgC ($TCRE_{5EgC}$), which was compared with the ratio of warming to emissions at doubled preindustrial CO_2 (approximately 1.4 EgC emissions) in the 1PCTCO2 simulations (TCRE; Figure 8b). Although there is variation in the ratio of warming to cumulative emissions for individual models, with the IPSL-CM5A-LR model showing a higher ratio at 5 EgC and the BCC-CSM 1.1 model a lower ratio, overall the mean ratio of warming to emissions across the four models was very similar at 5 EgC (1.63°C EgC^{-1}) compared to the ratio of warming to emissions at approximately 1.40 EgC (1.67°C EgC^{-1}) (Gillett et al., 2013). Thus, overall in these Earth system models, there is no evidence of the pronounced decrease in the ratio of CO_2-attributable warming to emissions at high emission levels seen in simple climate carbon models (Allen et al., 2009) and some EMICs (Zickfeld et al., 2013).

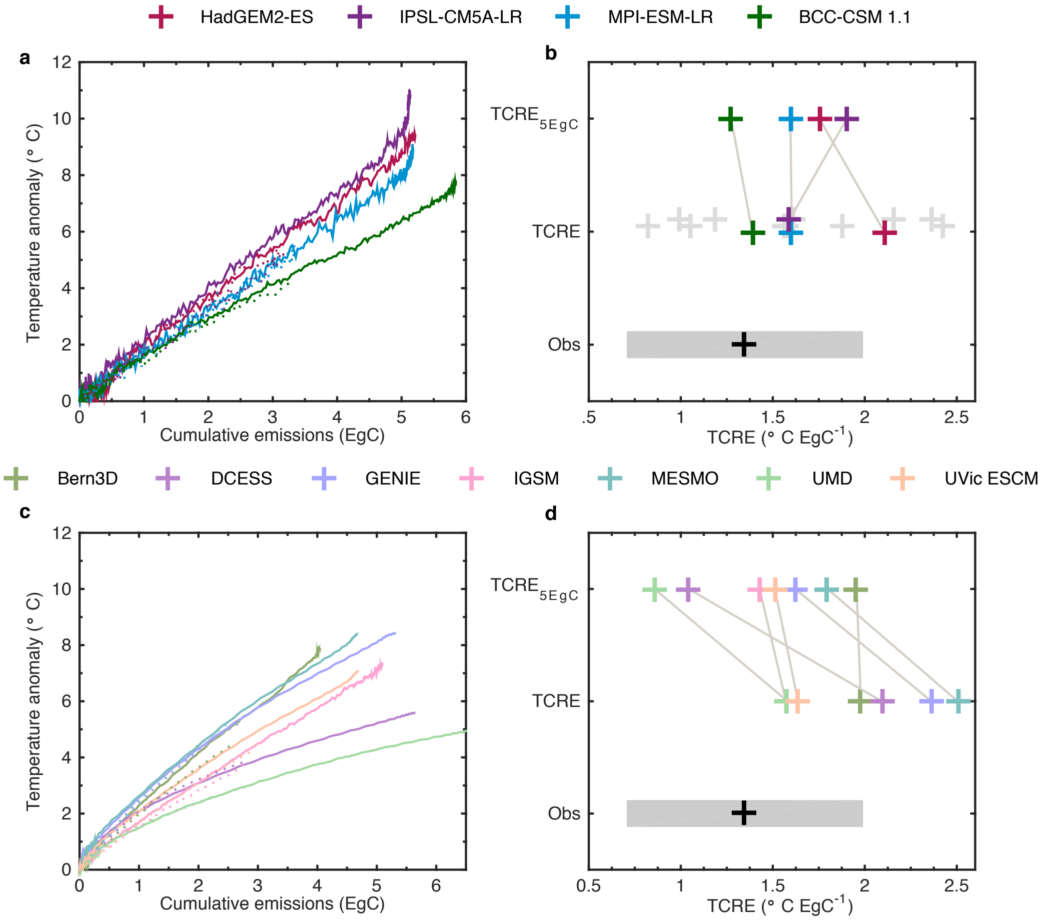


Figure 8. CO_2 -attributable warming as a function of cumulative CO_2 emissions, and the resulting ratio of warming to emissions for CMIP5 ESMs and EMICs.
Left panels: Simulated CO_2-attributable warming as a function of cumulative emissions based on historical and RCP 8.5-Ext (solid) and 1 % CO_2 increase simulations (dotted) from CMIP5 models (a), and EMICs (c). Right panels: the ratio of CO_2-attributable warming to cumulative emissions at 5 EgC emissions ($TCRE_{5EgC}$, top row) for CMIP5 models (b) and EMICs (d), compared with TCRE for respective models and other CMIP5 models (middle row; Gillett et al., 2013), and an observationally-constrained estimate of TCRE range (bottom row; Gillett et al., 2013).

TCRE: CMIP5 comparison with EMICs

A comparison of these results with simulations from a range of Earth system Models of Intermediate Complexity (EMICs) (Eby et al., 2013; Zickfeld et al., 2013) indicates all seven EMICs considered have a $TCRE_{5EgC}$ that is lower than their TCRE (Figure 8d), and that departures from a linear relationship between warming and cumulative emissions are on average larger for the EMICs than for the ESMs (Figure 9).

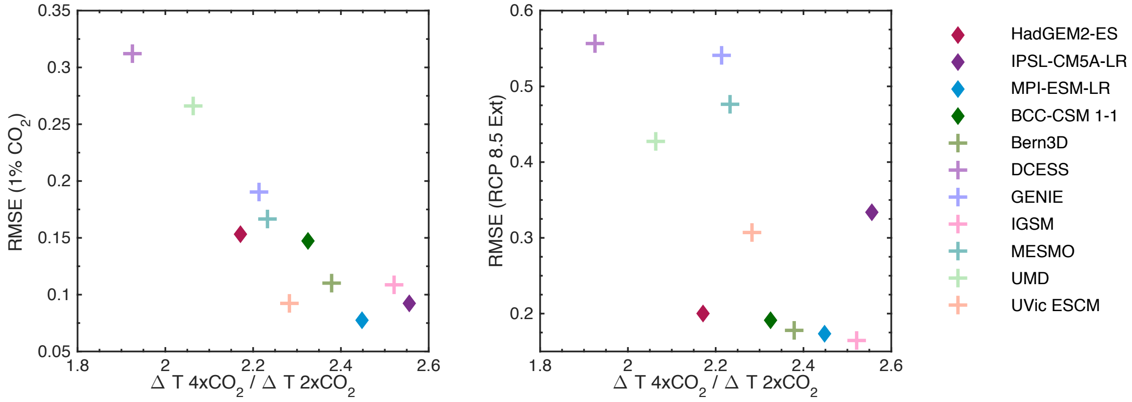


Figure 9. Root mean squared error (RMSE) and warming ratio at high cumulative emissions for 1PCTCO2 simulation (panel a) and RCP 8.5 Ext (panel b). The horizontal axis shows the ratio of warming in response to an increase in CO_2 concentration in a 1PCTCO2 simulation, where $1xCO_2$ is preindustrial CO_2 concentration. The ratio represents the warming in response to CO_2 concentration increase from $1xCO_2$ to $4xCO_2$, to the warming in response to CO_2 concentration increase from $1xCO_2$ to $2xCO_2$.The vertical axis shows root mean squared error for the least square linear regression fits to warming against cumulative emissions for the 1PCTCO2 simulation (panel a) and for the RCP 8.5 Extension pathway (after scaling by ratio of CO_2 to total radiative forcing) (panel b).

Figure 9 shows the root mean squared error (RMSE) calculated from a linear fit to a TCRE plot (for 1PCTCO2 simulations in panel a, and RCP 8.5 simulations in panel b), as a function of warming ratio at the time of CO_2 quadrupling to doubling ($\Delta T_{4xCO2}/\Delta T_{2xCO2}$; horizontal axis). If warming radiative forcing were proportional to the logarithm of the CO_2 increase, and if the temperature response were proportional to the radiative forcing, and disregarding any effects of the evolution of the CO_2 prior to the start of the averaging periods, then the warming ratio should be 2. A few EMICs (such as UVic ESM, IGSM, and Bern3D) show responses close to the ones modelled by CMIP5 models: having a low RMSE ratio (corresponding to an approximately linear TCRE plots), and showing a warming fraction ($\Delta T_{4xCO2}/\Delta T_{2xCO2}$) larger than 2, implying that those models warm more at the time of second CO_2 doubling (i.e. quadrupling). Models that warm more (per unit of CO_2 emitted) at high atmospheric CO_2 concentration levels, have a smaller root mean squared error (RMSE) deviation from the linear fit to their TCRE plots (Figure 9). Conversely, three EMICs (DCESS, UMD and GENIE) that warm the least (per unit of CO_2 emitted), have a large RMSE (hence, deviating more from a linear TCRE plot), compared to other models. These conclusions are in line with a recent study of Gregory et al., (2015), who analysed data for more ESMs for 1PCTCO2 simulations (up to 2000 GtC), also showing that ESMs tend to warm more per unit of cumulative emissions at the time of second CO_2 doubling.

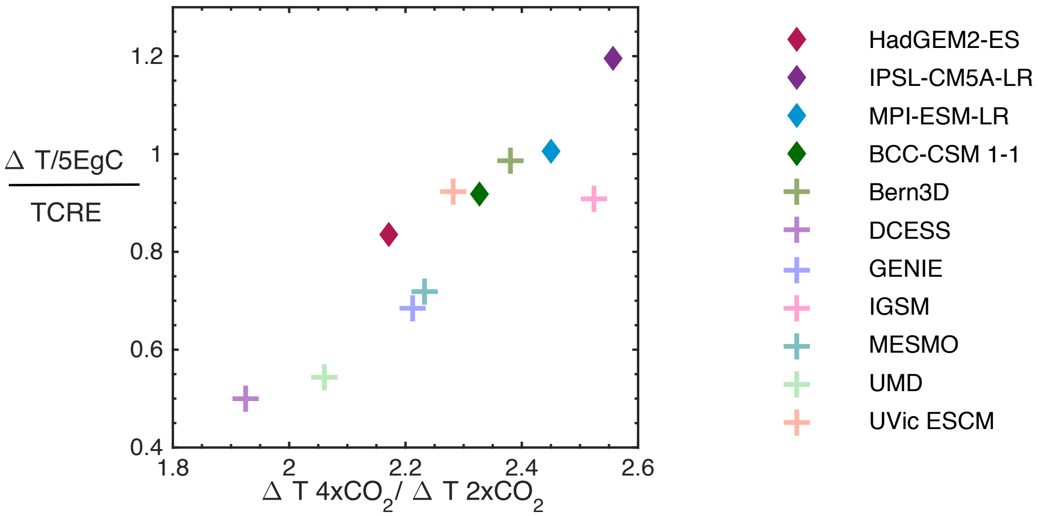


Figure 10. Ratio of warming at 5 EgC (from RCP 8.5 Ext simulation) to TCRE as a function of the warming ratio of temperature at CO_2 quadrupling to temperature at CO_2 doubling (from 1PCTCO2 increase simulations). ESMs are represented by diamonds, while EMICs are represented by crosses.

Figure 10 demonstrates that the ratio of TCRE_{5EgC} to TCRE is linearly related to the ratio of warming at four times preindustrial CO_2 to double preindustrial CO_2 in a 1PCTCO2 simulation across the ensemble of ESMs and EMICs that are considered, and that this warming ratio is substantially greater than two in all four ESMs considered here (Gregory et al., 2015). Moreover, the two EMICs, which do not contain a 3-dimensional ocean model (UMD and DCESS), are outliers both in terms of having a low warming ratio, and a low ratio of TCRE_{5EgC} to TCRE (Figure 10), consistent with previous work indicating that the enhancement of warming per unit forcing at higher forcing levels in CMIP5 ESMs is primarily a result of weakening heat fluxes into the deep ocean (Gregory et al., 2015), which are unlikely to be well-represented in these models. Consistent with our suggestion that differences in ocean heat uptake are important, there are systematic differences in the fraction of realised warming in the EMICs considered here and the CMIP5 ESMs in a 1PCTCO2 simulation, which have been attributed to differences in the profile of ocean heat uptake between the two classes of models (Frölicher & Paynter, 2015).

It has previously been suggested that at high emissions the logarithmic dependence of the radiative forcing on the CO_2 concentration is likely to dominate increases in the airborne fraction of CO_2 at high cumulative emissions to give a decrease in the ratio of warming to emissions (Collins et al., 2013; Gillett et al., 2013). These results, however, suggest that in these CMIP5 ESMs decreasing atmosphere-ocean heat fluxes (Gregory et al., 2015) combined with positive carbon-climate feedbacks, which increase the cumulative airborne fraction (Figure 11), compensate for the radiative forcing effect to keep this ratio approximately linear even at high cumulative emissions. Besides the role of a stronger decrease in the efficiency of ocean heat uptake with warming in the ESMs compared to the EMICs (Frölicher & Paynter, 2015; Gregory et al., 2015), a more rapid than logarithmic increase in CO_2 radiative forcing or a decline in climate feedback parameter at higher warming levels in the ESMs (Gregory et al., 2015) could also contribute to driving their relatively higher levels of warming at high cumulative emissions. Additional simulations would be required to test and distinguish these hypotheses.

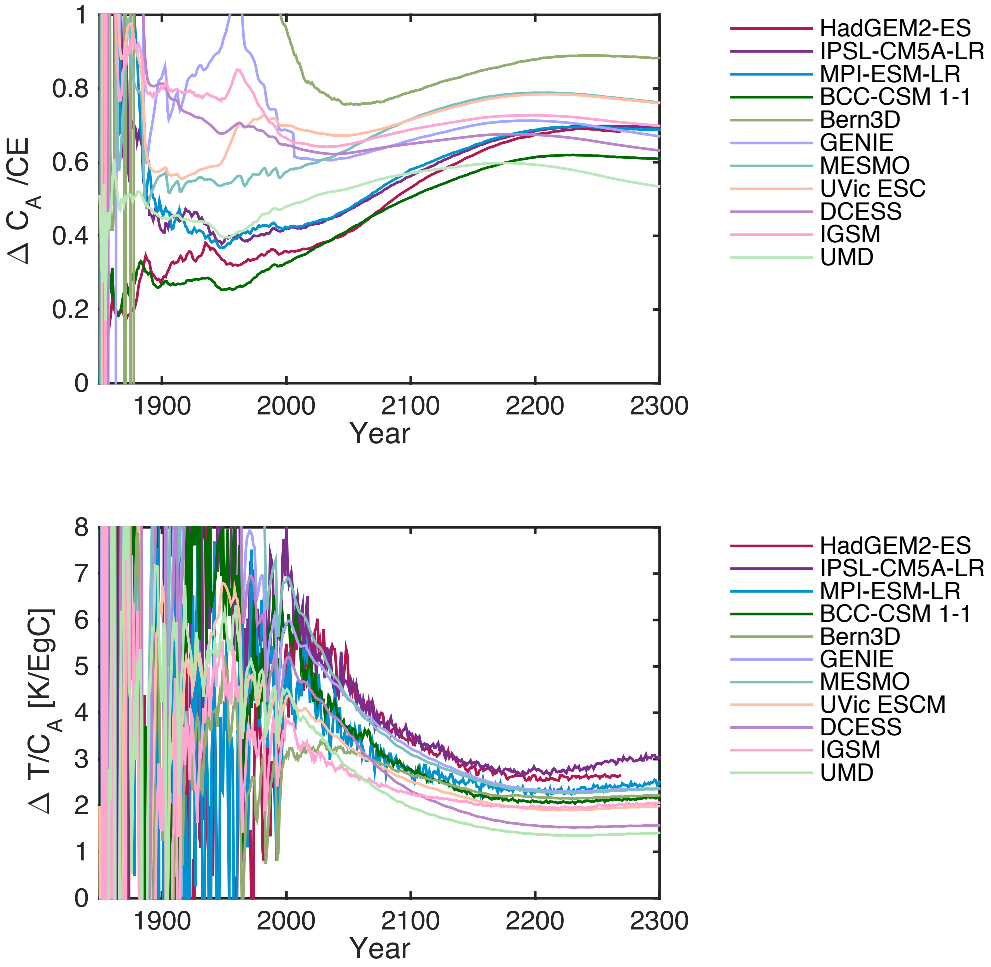


Figure 11. Atmospheric carbon burden in the RCP 8.5-Ext simulations, calculated as the change in atmospheric carbon (CA) per unit of cumulative carbon emissions (CE) (a); The ratio of temperature change (ΔT) to airborne fraction of CO_2 simulated in the RCP 8.5-Ext simulations (CA), as a function of time. Calculated as change in temperature per unit of atmospheric carbon (b).

Note that the product of these two ratios (CA /CE and ΔT/ CA) is equal to the ratio of temperature change to cumulative emissions.

CO_2-attributable warming: comparison with other studies

This study showed that simulated CO_2-attributable global mean warming in response to 5 EgC emissions, a representative estimate of eventual carbon emissions in the absence of any climate change mitigation policy, ranges from 6.4-9.5°C across four Earth system models, with a mean of 8.2°C. This warming estimate is higher than that predicted in previous studies based on simpler models (Allen et al., 2009; Zickfeld et al., 2013). A Monte Carlo estimate based on a simple carbon climate model tuned to reproduce the behaviour of the C4MIP models at low cumulative emissions predicted most likely warming of about 5°C for 5 EgC emitted to the atmosphere (Allen et al., 2009). An EMIC inter-comparison study reports a global mean warming of 7.8°C (ranging from 4.7°C to 9.8°C) for RCP 8.5 pathway in year 3000 relative to 1986-2005, where the diagnosed cumulative emissions range from approximately 4.3 EgC to 11.3 EgC relative to the same base period (Zickfeld at al., 2013), and a warming of 8.9°C was simulated in response to 5.3 EgC emissions, by the UVic EMIC (Herrington and Zickfeld, 2014).

The four CMIP5 models considered here exhibit warming in 2281-2300 under RCP 8.5-Ext towards the upper end of the CMIP5 range, and their TCRE are all above the best estimate from observations (Figure 8b; where the observational TCRE estimate is from Gillett et al., 2011). However, if the simulated warming from HadGEM2-ES is discounted on the basis that its TCRE is outside the estimated 5-95% range estimated from observations (Figure 8b), the warming range at 5 EgC from the remaining three models, whose TCRE are well-within the observationally-constrained range, is unchanged. If suitable simulations were available from a broader range of CMIP5 ESMs, the lower end of the simulated warming at 5 EgC would be expected to be extended downwards, but there is no reason to discount the upper end of the warming range simulated by the models considered here based on observational constraints. Accounting for the effects of other forcings as in the RCP 8.5-Ext scenario increases the mean warming at 5 EgC emissions to 9.7°C.

It is important to emphasize that EMICs represent a very diverse group of models, some of which (e.g. Bern3D and UVic ESCM) have a three-dimensional ocean, and demonstrate behaviour similar to ESMs, as discussed before. Since deviations from a linear relationship between warming and cumulative emissions at high emissions are likely to be particularly sensitive to ocean heat and carbon uptake, it is likely that a different choice of parameters for the carbon cycle, ocean heat uptake, and diffusion, could result in a more linear TCRE slope in those models. For example, altering the ocean mixing parameters in the UVic model makes it possible to represent responses of CMIP5 ESMs (MacDougall et al., 2017). However, some EMICs (e.g. UMD or DCESS) have a simpler representation of the ocean, or use a two-layer slab ocean model. In such cases, the missing key ocean mixing processes responsible for ocean carbon and heat uptake are likely to be unrealistic, consequently, they are unlikely to result in a proportionality of warming to cumulative emissions. Therefore, we would suspect fundamental differences between some simpler EMICs and the CMIP5 ESMs.

2.4.3. Regional climate change

Temperature and Precipitation at 5 EgC

In response to emissions of 5 EgC, the Earth will encounter a profound climate change, with the global mean CO_2-attributable warming ranging between 6.4 and 9.5°C. The regional warming could be even more severe, with the Arctic warming ranging between 14.7 and 19.5 °C, in a response to five trillion tonnes of carbon emitted (Figure 12a). Individual model responses are shown in Figure 13.

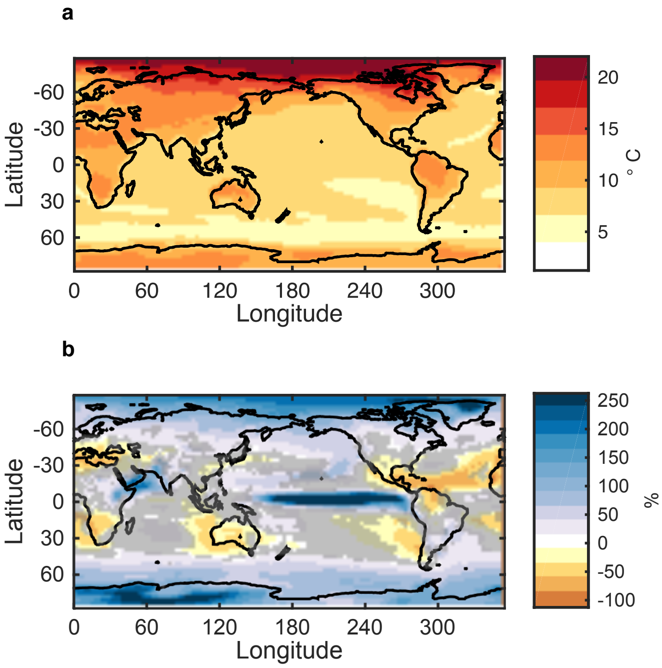


Figure 12. Simulated model-mean temperature and precipitation changes in response to 5 EgC emissions.
Multi-model mean temperature change in response to 5 EgC CO_2 emissions, with respect to the preindustrial control simulation (a). Multi-model mean precipitation response to 5 EgC CO_2 emissions, expressed as a percentage of simulated preindustrial precipitation (b). The values correspond to the time when cumulative emissions reach 5 EgC, and are scaled by the ratio of CO_2 to total radiative forcing. Grey shading indicates regions of inconsistent model responses, where at least one model shows a change of opposite sign than the model-mean.

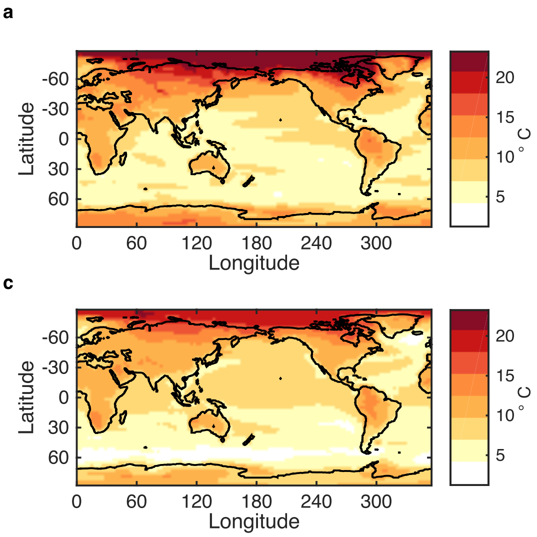


Figure 13. Regional temperature response to 5 EgC CO_2 emissions, anomaly with respect to the preindustrial control simulation, for different models: HadGEM2-ES (a); IPSL-CM5A-LR (b); MIP-ESM-LR (c); BCC-CSM 1.1 (d).The values correspond to the time when cumulative emissions reach 5 EgC, and are scaled by the ratio of CO_2 to total radiative forcing.

Simulated mean changes in precipitation associated with 5 EgC emissions are extremely large (Figure 12b; Figure 14), with local mean precipitation increases exceeding a factor of four in the tropical Pacific and decreases by more than a factor of two over parts of Australia, the Mediterranean, southern Africa and the Amazon, and a factor of three in central America and North Africa. The very high increase in precipitation in equatorial region (Figure 14) occurs primarily due to changes in atmospheric circulation, and increased in water vapour content (Hegerl, et al., 2007). The pattern of temperature and precipitation changes per degree of global mean warming is similar in 2300 to 2100 (Figure 15), and hence likely driven by the same mechanisms (Chadwick et al., 2013; Collins et al., 2013). Differences between these patterns such as enhanced warming of the high latitude Southern Hemisphere and relatively larger precipitation increases in 2300 are consistent with the radiative forcing having stabilized near the end of the simulation (Collins et al, 2013).

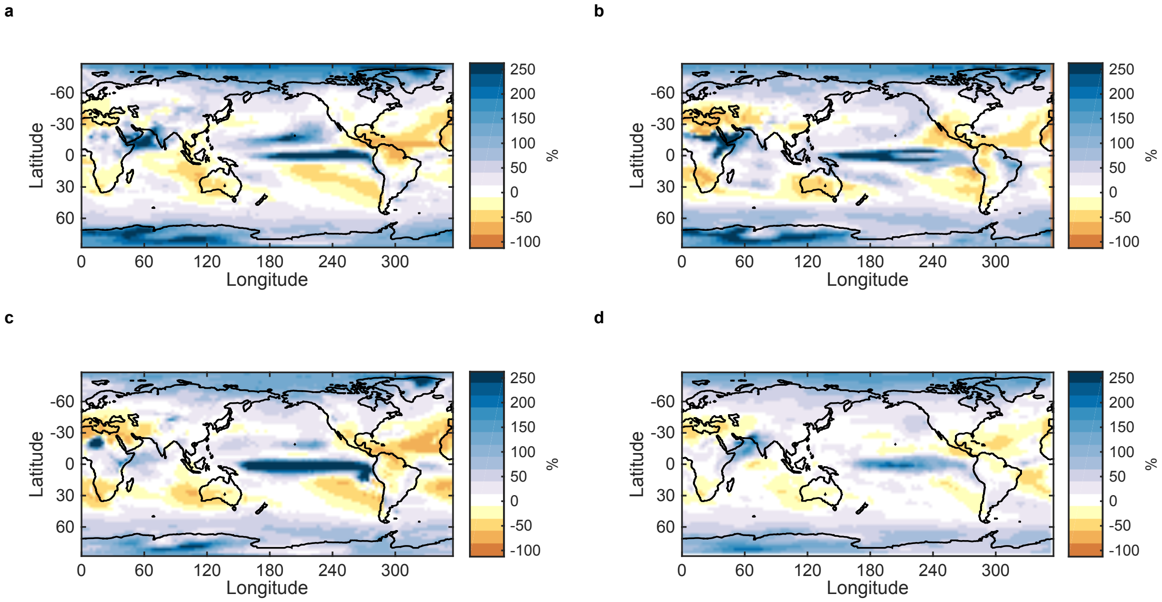


Figure 14. Regional precipitation response to 5 EgC CO_2 emissions, expressed as a percentage of simulated preindustrial precipitation for different models: HadGEM2-ES (a); IPSL-CM5A-LR (b); MIP-ESM-LR (c); BCC-CSM 1.1 (d). The values correspond to the time when cumulative emissions reach 5 EgC, and are scaled by the ratio of CO_2 to total radiative forcing.

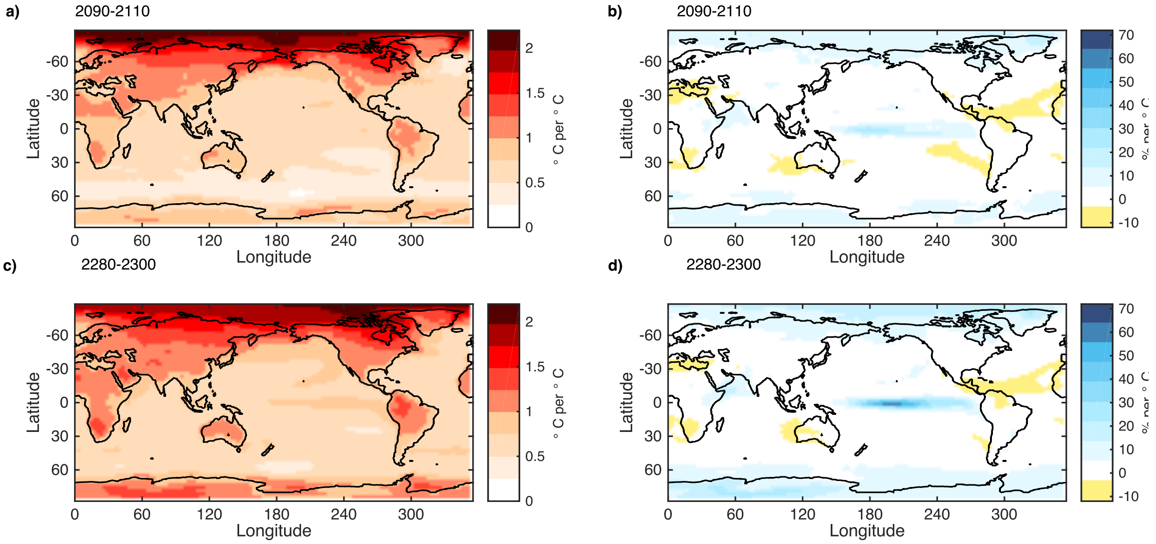


Figure 15. Simulated model-mean CO_2-attributable temperature (left) and precipitation changes (right) for the period 2090-2110 (top) and 2080-2300 (bottom), scaled by the global mean temperature in respective year. Precipitation is expressed as a percentage of simulated preindustrial precipitation. Anomalies are relative to preindustrial control run.

2.5. Discussion and Conclusions

Using simulations from four comprehensive Earth system models, this study demonstrates that CO_2-attributable warming continues to increase approximately linearly up to 5 EgC emissions. These models simulate, in response to 5 EgC of CO_2 emissions, global mean warming of 6.4-9.5 °C (due to CO_2 alone), mean Arctic warming of 14.7-19.5 °C, and mean regional precipitation increases by more than a factor of four. These results also show that five trillion tonnes of cumulative carbon emissions, corresponding approximately to the unregulated exploitation of the fossil fuel (Moomaw et al., 2011; Cowie, 2013; Henderson-Sellers & McGuffie, 2011), could result in considerably larger global and regional climate changes than previously suggested (Allen et al., 2009; Zickfeld et al., 2013). Such climate changes, if realized, would have extremely profound impacts on ecosystems, human health (Sherwood & Huber, 2010), agriculture, economies and other sectors (IPCC, 2014).

In contrast to the results of previous studies using simpler models, this study showed that in comprehensive Earth system models global mean warming increases close to linearly with cumulative carbon emissions even up to 5 trillion tonnes of carbon emitted, due to approximately cancelling nonlinear behaviour in the physical climate system and carbon cycle. This study showed that some EMICs tend to exhibit a reduced rate of warming as cumulative emissions increase, leading to a decline in a relationship between warming and cumulative carbon emissions. Conversely, comprehensive ESMs continue to show approximately linear relationship between warming and cumulative carbon emissions. This linearity, which continues to hold even at high levels of carbon emitted in the ESMs, is likely to be associated with stronger decreases in the efficiency of ocean heat uptake with warming in the ESMs, consistent with other recent studies (Frölicher & Paynter, 2015; Gregory et al., 2015). However, other processes, such as a more rapid than logarithmic increase in CO_2 radiative forcing or a decline in climate feedback parameter at higher warming levels in the ESMs could also play a role (Gregory et al., 2015). This implies that the assumption of a constant ratio of warming to cumulative CO_2 emissions is a reasonable assumption for cumulative CO_2 emissions up to 5 EgC, and hence, that proposed regulatory frameworks based on cumulative CO_2 emissions (Frame et al, 2014; IPCC, 2014) are robust over a wide range of plausible CO_2 scenarios.

Chapter 3. Project II: Understanding the influence of non-CO_2 forcings on cumulative emission budgets

This chapter is based on the contents of the paper:

Tokarska, K.B., Gillett, N.P., Arora, V.K., Lee, W., and Zickfeld, K. (2017). The influence of non-CO_2 forcings on cumulative carbon budgets. (in review).

3.1. Introduction and Motivation

The approximately linear relationship between warming and the total amount of carbon emitted (also referred to as the transient climate response to cumulative emissions or TCRE) is shown in Figure 16, both for comprehensive Earth System models (CMIP5) and for Earth System Models of intermediate complexity (EMICs). The red shaded area represents model spread (90% range) in response to the RCP 8.5 scenario, which includes CO_2 and non-CO_2 forcings (Figure 17), while the grey shaded area shows the model spread in response to CO_2-only simulations, in which the atmospheric CO_2 concentration increases at a rate of 1% per year until the time of CO_2 doubling. The difference between the grey and red shaded areas indicates the effect of non-CO_2 forcing on temperature. Since the non-CO_2 forcings have a net warming effect in the RCP 8.5 scenario (Figure 17), the red shaded area is above the grey one (Figure 16).

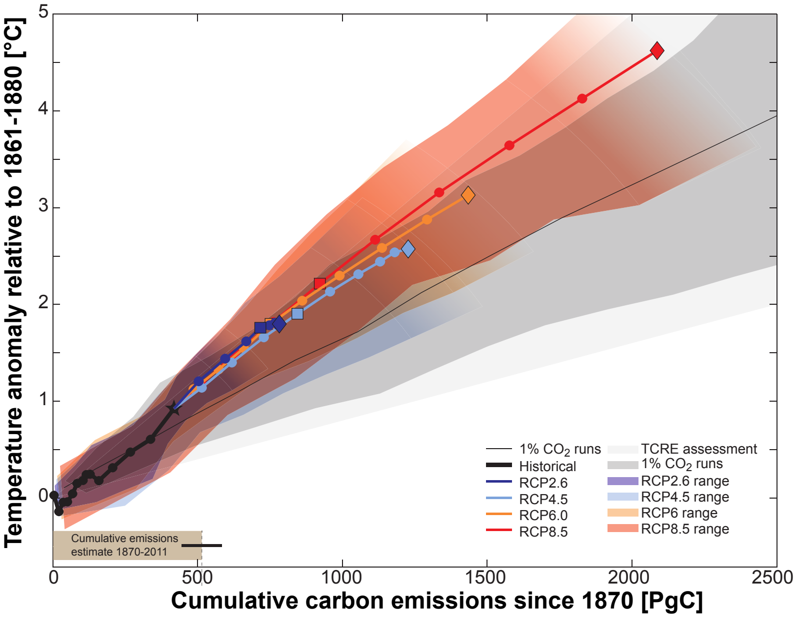


Figure 16. Global mean temperature increase as a function of cumulative carbon emissions (IPCC AR5, 2013, TFE.8, Figure 1a).
The red shaded area shows the model spread (90% range) under RCP 8.5 scenario (based on ESMs and EMICs responses). The grey shaded area shows model responses to a 1PCTCO2 scenario, where the atmospheric CO_2 concentration increases at a rate of 1% per year until doubling of the pre-industrial CO_2 level. The coloured lines indicate model responses to different RCP scenarios, as identified in the legend.

Based on Figure 16, the IPCC Summary for Policymakers (IPCC 2013, Summary for Policymakers p.27) reported carbon budgets, or the total amount of carbon that could be emitted in order not to exceed the global mean temperature level of 2°C above the 1860-1880 period, when considering CO_2 -only forcing alone, and when accounting for non-CO_2 forcings:

> *“Limiting the warming caused by anthropogenic* CO_2 *emissions alone with a probability of >33%, >50%, and >66% to less than 2°C since 1861-1880 will require cumulative* CO_2 *emissions from all anthropogenic sources to stay between 0 and 1570 GtC, 0 and 1214 GtC and 0 and about 1000 GtC since that period, respectively. These upper amounts are reduced to about 900GtC, 820GtC and 790 GtC, respectively, when accounting for non-*CO_2 *forcings as in RCP 8.5. An amount of 515 [445 to 585] GtC was already emitted by 2011” (IPCC 2013, Summary for Policymakers, p.27).*

In the excerpt from the IPCC *Summary for Policymakers* cited above, carbon budgets based on CO_2 forcing alone were inferred from an estimate of the transient climate system response to cumulative carbon emissions (TCRE) and observations, and widely range from 1000 to 1570 PgC (range of 570 PgC) emitted for limiting the warming to less than 2 ºC since 1861-1880 due to carbon dioxide alone (with the probability of not exceeding that temperature threshold > 66% and >33%, respectively). Carbon budgets calculated directly from simulations that include forcing from both CO_2 and non-CO_2 greenhouse gases (such as the RCP 8.5 scenario; Figure 17), result in about five times as narrow range of cumulative carbon emissions consistent with the same temperature threshold and for the same probabilities range, ranging from 790 to 900 PgC (range of 110 PgC), as reported by IPCC AR5 (text above).

Non-CO_2 forcings have a net warming effect in the future under RCP 8.5 scenario (Figure 17), leading to a reduction in carbon budgets associated with given warming targets. Due to the additional warming from the non-CO_2 greenhouse gases, natural terrestrial and marine carbon sinks will be reduced, associated with the positive carbon-climate feedback (Gillett & Matthews, 2010; MacDougall and Knutti, 2016).

The reductions in carbon budgets due to non-CO_2 forcing can be separated into some combination of two distinct effects: the direct climate warming effect of the non-CO_2 forcings, and the carbon cycle response to the additional warming caused by the non-CO_2 greenhouse gases (Gillett and Matthews, 2010). A recent study using a climate model of intermediate complexity (MacDougall et al., 2015), has shown reductions in the 2 °C carbon budget ranging from 313 to 485 PgC due to the net effect of non-CO_2 greenhouse gases affecting the climate warming and carbon cycle feedbacks, which also include permafrost feedbacks that further exacerbate the effects of carbon cycle feedbacks at higher temperatures.

This project aims to quantify the impact of non-CO_2 forcing on cumulative carbon budgets, firstly, using a comprehensive Earth System Model (CanESM2; Section 3.4.1), and secondly, by extending the analysis to a multi-model framework, using output from other comprehensive Earth System Models (CMIP5; Section 3.4.2). The differences between the carbon budgets based on CO_2-only simulations, and simulations which also include non-CO_2 forcing (referred to as ALL-forcing), are assessed, and effects contributing to the differences in ranges between CO_2-only and ALL-forcing carbon budgets are explained.

3.2. Research Questions

The key research questions this project addresses are:

- What is the magnitude of the impact of non-CO_2 forcings on cumulative carbon budgets in the CanESM2 model, and how much of it occurs due to the climate warming effects, and how much due to the combined effects of carbon-cycle feedbacks and land use change?
- What are the impacts of non-CO_2 forcing on carbon budgets for other CMIP5 models based on their RCP 8.5 and 1PCTCO2 simulations to provide better estimates of the impact of non-CO_2 forcing on the IPCC carbon budgets?
- What effects contribute to the wide range of CO_2-only carbon budgets and a much narrower range on carbon budgets based on simulations that include both CO_2 and non-CO_2 forcings, as reported by IPCC AR5?

3.3. Methods

3.3.1. Models and scenarios

This project makes use of simulations from eleven comprehensive Earth system models (ESMs) from the Fifth Coupled Climate Model Intercomparison Project (CMIP5; Taylor et al., 2012), driven by specified concentrations of CO_2 and other greenhouse gases for the historical period and for the future period represented by the Representative Concentration Pathway 8.5 (RCP 8.5) scenario (van Vuuren et al., 2011; Meinshausen et al., 2011), which reaches a radiative forcing level of 8.5 W/m^2 by 2100, and includes forcing from both CO_2 and non-CO_2 agents (such as methane, nitrous oxide, halocarbons and aerosols; Figure 17). To compare cumulative carbon emissions calculated from this ALL-forcing simulation with cumulative carbon emissions from simulations that include CO_2-forcing alone, a custom set of CO_2-only simulations forced solely by the CO_2, which evolves according to the RCP 8.5 scenario was conducted, using the second generation Canadian Earth System Model (CanESM2). Extension of those results to a multi-model framework including other CMIP5 models and a description of methodology used is presented in Section 3.4.2.

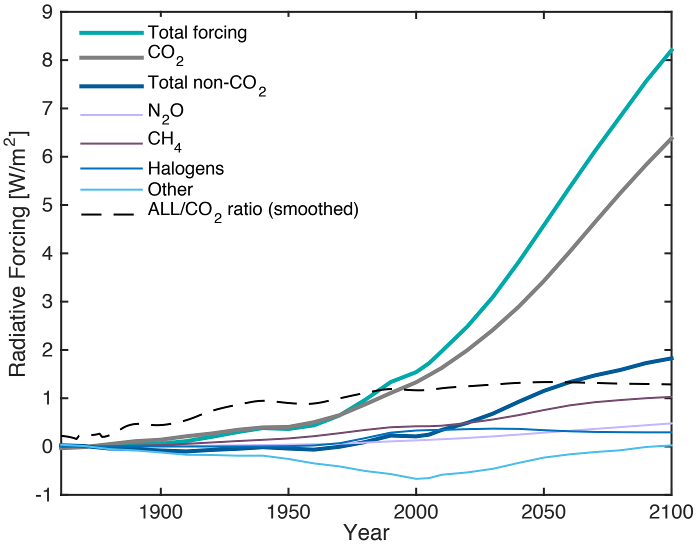


Figure 17. Time series of individual radiative forcing components in RCP 8.5. scenario. (based on van Vuuren et al., 2011).Total forcing is a sum of all forcings presented in this figure, while total non-CO_2 forcing is a sum of all forcings other than the CO_2 forcing.

3.3.2. Carbon budget calculations

Fossil fuel emissions and total carbon emissions

Following notation in Arora et al., 2013, the rate of change of carbon exchange between atmosphere, land, and ocean can be expressed by:

$$E_F = \frac{dH_A}{dt} + \frac{dH_L}{dt} + \frac{dH_O}{dt} \tag{3.1}$$

where E_F is the fossil fuel emission rate, $\frac{dH_L}{dt}$ and $\frac{dH_O}{dt}$ are the atmosphere-land, and atmosphere-ocean carbon fluxes, respectively, and $\frac{dH_A}{dt}$ is the rate of change of the atmospheric carbon with time (Arora et al., 2013). Most of the Earth System Models considered here (unless otherwise noted) include interactively modelled land-use change emissions that are determined by specified changes in the land cover (Arora et al., 2011).

The atmosphere-land carbon flux $\frac{dH_L}{dt}$ can be expressed then as the natural land carbon flux component $\frac{dH_{l(nat)}}{dt}$, which itself is a function of land use, and the anthropogenic land use change emissions E_{LUC} (Arora et al., 2011), indicated in Equation 3.2 below:

$$\frac{dH_L}{dt} = \frac{dH_{l(nat)}}{dt} - E_{LUC} \tag{3.2}$$

The total anthropogenic emission rate E_{total} can be then expressed as a sum of the fossil fuel emissions E_F and land-use change emissions E_{LUC}. Since $\frac{dH_{l(nat)}}{dt}$ cannot be directly diagnosed from the model output, but $\frac{dH_L}{dt}$ can be diagnosed, the total emissions estimate (E_F +E_{LUC}) is then:

$$E_{total} = (E_F + E_{LUC}) = \frac{dH_A}{dt} + \frac{dH_{l(nat)}}{dt} - E_{LUC} + \frac{dH_O}{dt} + E_{LUC} \tag{3.3}$$

And hence:

$$E_{total} = (E_F + E_{LUC}) = \frac{dH_A}{dt} + \frac{dH_L}{dt} + \frac{dH_O}{dt} + E_{LUC} \tag{3.4}$$

Equivalently, Eq. 3.4 follows directly from Eq. 3.1 by adding E_{LUC} to each side.

Cumulative carbon emissions

Cumulative carbon emissions (*CE*) can then be calculated by addition of the net time-integrated atmosphere-land $\int \frac{dH_L}{dt} dt$ and atmosphere-ocean $\int \frac{dH_o}{dt} dt$ carbon fluxes with the time-integrated rate of change of atmospheric carbon $\int \frac{dH_A}{dt} dt$. For prescribed concentration simulations, $\int \frac{dH_A}{dt} dt$, and $\frac{dH_A}{dt}$ follow the values as specified by the given RCP scenario (Arora et al., 2011). Conversely, cumulative carbon emissions (CE) can be expressed in terms of the global carbon pool:

$$CE = \int\ E_{total}\, dt = \ \Delta H_A + \Delta H_L + \Delta H_o + \int E_{LUC}\, dt \tag{3.5}$$

where *E* is the anthropogenic emission rate, and ΔH_A, ΔH_L, and ΔH_O is the change in atmosphere, land, and ocean carbon pool, respectively, in PgC (as in Arora et al., 2013). The change in atmospheric carbon pool ΔH_A is prescribed according to the given RCP concentration pathway. The anthropogenic land use change emissions (E_{LUC}) were specified in the RCP database (van Vuuren et al., 2011), and these estimated emissions were added to each model's diagnosed fossil fuel emissions to calculate total cumulative carbon emissions (E_{total}), since E_{LUC} could not be diagnosed directly from the standard CMIP5 model output. For CanESM2, we used additional simulations (with and without land use change), to directly calculate the land use change in that model (as discussed later in Section 3.4.5).

Carbon budget and radiative forcings ratios

Cumulative emissions budgets (*CEB*) are the cumulative carbon emissions (at a specific point in time), consistent with limiting anthropogenic warming to below a given temperature threshold (e.g. 1.5 °C or 2.0 °C, as specified in text). Carbon budgets calculated from CO_2-only simulation (when that simulation reaches the given temperature threshold in the year following t_{CO_2}) are denoted as CEB_{CO_2}, and carbon budgets calculated from ALL-forcing simulation (when that simulation reaches the given temperature threshold in the year following t_{ALL}) are denoted as CEB_{ALL}. The ratio in carbon budgets between the CO_2-only simulation and ALL-forcing simulation that includes both CO_2 and non-CO_2 forcings is then:

$$carbon\ budget\ ratio = \frac{CEB_{ALL}}{CEB_{CO_2}} \tag{3.6}$$

Since radiative forcings in the RCP 8.5 scenario change over time (Figure 17), the ratio of radiative forcings (ALL-radiative forcing and CO_2-only radiative forcing) was calculated as follows:

$$radiative\ forcing\ ratio = \frac{RF_{ALL}(t_{CO_2})}{RF_{CO_2}(t_{CO_2})} \tag{3.7}$$

where *RF* denotes respective radiative forcing, and t_{CO_2} is the year before the CO_2-only simulation reaches the given temperature target (e.g. 1.5 °C or 2.0 °C, specified in text).

3.3.3. Cumulative frequency distributions of carbon budgets

Cumulative frequency distributions of carbon budgets (shown later in Figure 23 of this chapter and Figure 31 in Chapter 4) were calculated as in Gillett, 2015, according to Eq. 3.8 and Eq. 3.9 below. The cumulative emissions budgets (CEB_i) simulated in individual ensemble members of all models considered are sorted in ascending order, and the cumulative frequency distribution is defined as:

$$C(CEB) = \sum_{l=1}^{l=L} w_l \tag{3.8}$$

where:

$$w_l = \frac{1}{I\,N_l} \tag{3.9}$$

and L is chosen such that $CEB_L < CEB < CEB_{L+1}$, since the cumulative emission budgets (*CEB*) are sorted in an ascending order, and L is then the index of the simulation (including all individual ensemble members). I is the number of models considered, and N_l is the size of the ensemble from which the l^{th} simulation is drawn. This approach uses all available ensemble members, but gives equal weight to each model (Gillett, 2015). If only one ensemble member is used from each model, it is identical to the approach used to generate a similar figure in the IPCC assessment (IPCC AR5: TFE.8, Figure 1).

3.4. Results

3.4.1. The impact of non-CO_2 forcings on carbon budgets in the Canadian Earth System Model (CanESM2)

Temperature in the ALL-forcings simulation is higher than in the CO_2-only simulation by year 2100, as expected, due to the net warming impact from the non-CO_2 forcings in RCP 8.5 scenario (Figure 18). However, during the historical period temperature is higher in the CO_2-only simulation, as the ALL-forcings simulation includes a strong negative forcing from the sulphate aerosols, having a net cooling effect, which is reduced in future simulation years in the RCP 8.5 scenario (Figure 17). Aerosol concentrations eventually decrease in all RCPs, following the strong decrease in anthropogenic SO_2 emissions (van Vuuren et al., 2011), likely due to implementation of regulations that address their adverse effects on health and environment (such as acid rain or respiratory problems).

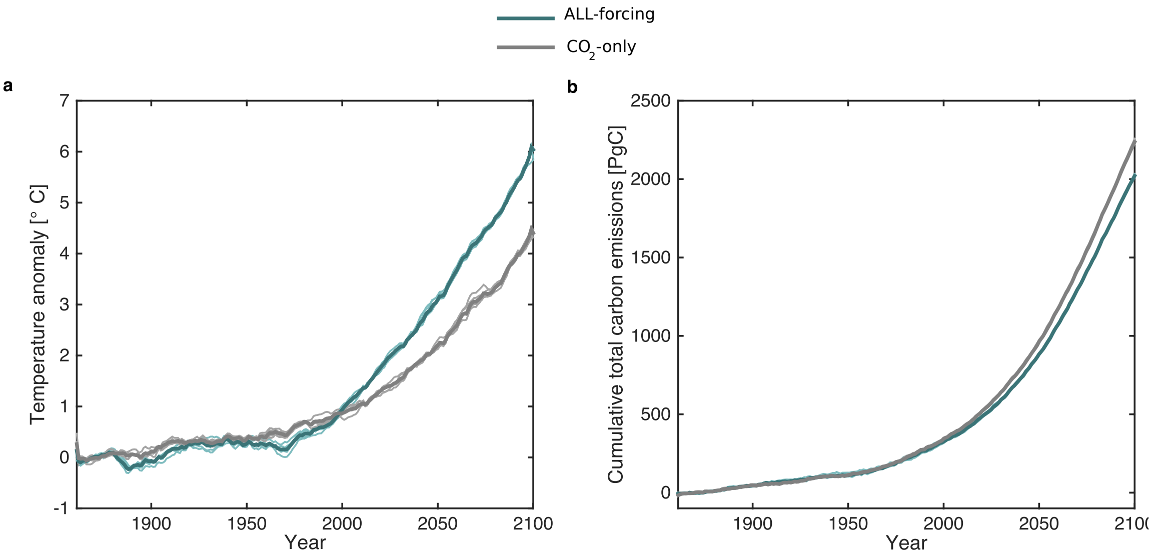


Figure 18. Time series of temperature (left) and cumulative carbon (right) in the ALL-forcing simulation (blue) and CO_2–only simulation (grey) under the RCP 8.5 scenario in CanESM2. Individual ensemble members for each simulation are shown by the light lines, while darker lines indicate ensemble means.

The cumulative carbon emissions (defined in Section 3.3.2) were calculated from the monthly mean output for each simulation by addition of the net atmospheric, land and ocean carbon anomalies. The total land and ocean carbon storage was calculated by integration of the atmosphere-land and atmosphere-ocean carbon fluxes, respectively.

The ALL-forcings simulation includes land use changes, which cannot be calculated directly from the model output. Therefore, an estimate of the cumulative land use change emissions from the prescribed land-use change RCP 8.5 scenario (from the RCP database, van Vuuren et al., 2011) has been added to the total cumulative emissions, in order to account for the carbon emissions from land use change that are simulated by the models forced with the RCP 8.5 scenario. Further description of uncertainties arising from land use change is in Section 3.4.6.

The total diagnosed cumulative carbon emissions (Figure 18) gradually increase over time in both simulations. Initially, the cumulative carbon emissions are higher in the

ALL-forcings simulation, however, by the end of the 21st century, the cumulative carbon emissions are slightly higher in the CO_2-only simulation, compared to the ALL-forcings simulation (Figure 18). This difference arises due to the combined effects of the land use change and the effects of non-CO_2 forcings on land and ocean carbon storage. Particularly, the differences are more pronounced in the terrestrial land carbon storage between these two simulations, which is higher in the ALL-forcings simulation during the historical period, followed by a slightly higher terrestrial carbon uptake in the CO_2-only simulation in the 21st century, due to lack of land use change emissions in that simulation (E_{LUC} in Eq. 3.2).

The differences between the ALL-forcings simulation and the CO_2-only simulation in the relationship between the temperature and the total amount of carbon emitted are illustrated in Figure 19. The red arrow indicates a reduction in a carbon budget consistent with not exceeding the 2.0 °C warming threshold due to the net warming effects of non-CO_2 forcings. Subsequently, the carbon budgets compatible with not exceeding different temperature targets (1.5 °C and 2.0 °C) have been calculated for both simulations (CO_2 -only and ALL-forcings simulation), and are shown later in Figure 21.

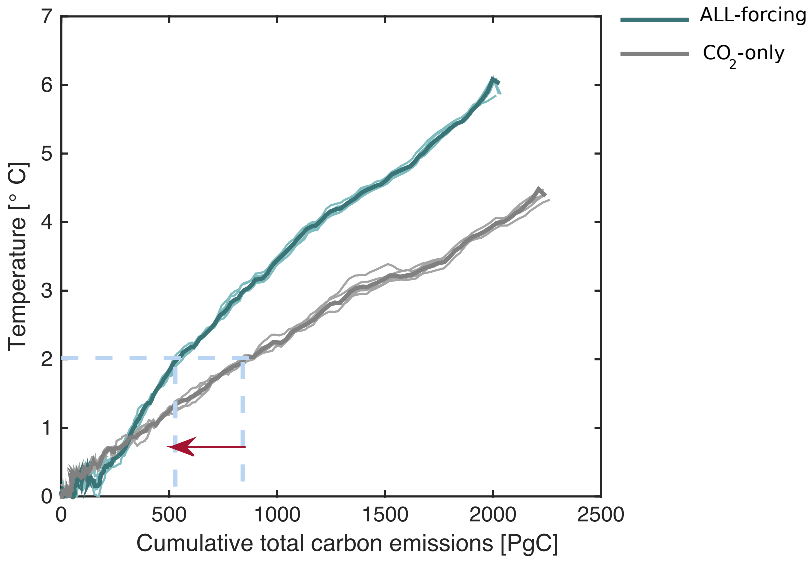


Figure 19. Warming as a function of cumulative carbon emissions in the RCP 8.5 ALL-forcings and CO_2 –only simulations from CanESM2.
The reduction in the carbon budget due to the net effects of non-CO_2 forcing for a 2°C temperature target is indicated by the red arrow. Individual ensemble members for each simulation are shown by the light lines, while darker lines indicate ensemble means.

The reduction in CO_2-only carbon budgets due to the net warming effects of the non-CO_2 forcing is illustrated in Figure 19. Greater reductions in the CO_2-only carbon budgets are needed for higher temperature targets, as the effect of non-CO_2 greenhouse gases on carbon budgets becomes stronger (due to declining aerosol forcing in RCP 8.5 scenario, Figure 17). There is not much difference expected from carbon budgets consistent with different levels of warming calculated from other RCP scenarios, as CO_2 is the dominant forcing in all RCP scenarios and the ratio of CO_2 to total forcing does not vary much across the RCP scenarios. Such conclusions can also be inferred from Figure 16, since the TCRE curve for all RCP scenarios overlay each other, especially at lower levels of warming, such as for 1.5 or 2.0 °C. Also, similar conclusions are supported by a recent study that uses an Earth system model of intermediate complexity to calculate carbon budgets for different RCP scenarios (MacDougall et al., 2015). Separation of the climate warming effects and the carbon cycle and land use change effects responsible for the carbon budget reductions in CanESM2 is further discussed in Section 3.4.5.

3.4.2. Extending the analysis to other CMIP5 models

Since the RCP 8.5 CO_2-only simulations are not available for comprehensive Earth System Models other than CanESM2, and based on the widely accepted theoretical framework that the relationship between warming and cumulative carbon emissions is approximately linear (IPCC, 2013, Collins et al., 2013, Gillett et al., 2013) and pathway independent (Zickfeld et al., 2009), the CO_2-only response for other ESMs was determined in the following way. Firstly, using the CanESM2 results, the CO_2-only temperature results were compared with the results from the 1PCTCO2 simulation, where the atmospheric CO_2 concentrations increase at a rate of 1% per year until CO_2-doubling (Gillett et al., 2013). Such temperature plots as a function of atmospheric CO_2 concentration and as a function of cumulative carbon emissions are shown in Figure 20, and they confirm that the 1PCTCO2 simulations may be used to approximate the temperature response in a RCP 8.5 CO_2-only simulation (Figure 20). This approximation is likely to hold most closely over periods in which CO_2 concentration is increasing at close to 1% per year, such as over recent decades and in the 21st century under the RCP 8.5 scenario. Secondly, carbon budgets consistent with the two warming thresholds (1.5 °C and 2.0 °C) inferred from the 1PCTCO2 simulations were compared with those calculated directly from RCP 8.5 CO_2-only simulation. The CO_2-only carbon budgets consistent with 2.0 °C warming threshold, calculated from 1PCTCO2 simulations, are within the range of the carbon budgets calculated from the RCP 8.5 CO_2-only simulations (five-member ensemble for CanESM2), as shown in Figure 21.

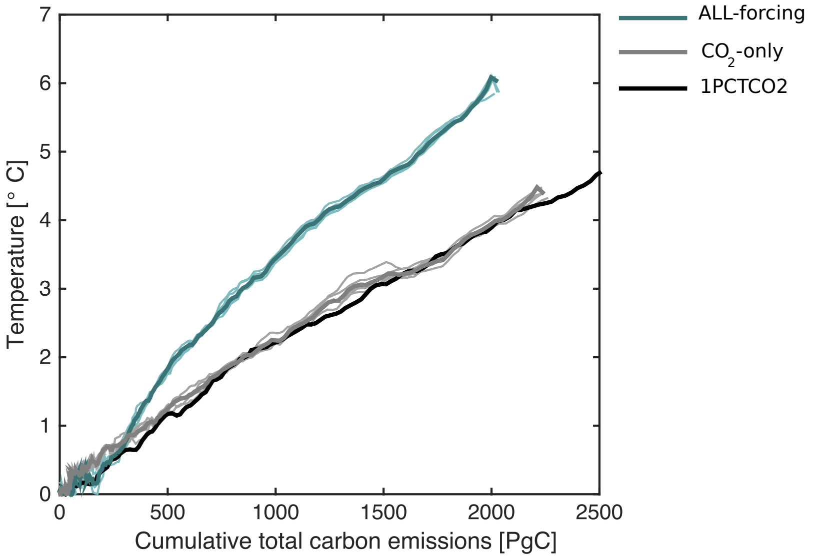


Figure 20. Temperature as a function of atmospheric concentration. Comparison of 1PCTCO2 simulations (black line), with CO_2-only runs (based on RCP 8.5 CO_2-only simulation; light gray), and ALL-forcings RCP 8.5 simulation (teal) in CanESM2. Individual ensemble members for each simulation are shown by the light lines, while darker lines indicate ensemble means. 1PCTCO2 simulation was based only on one available ensemble member.

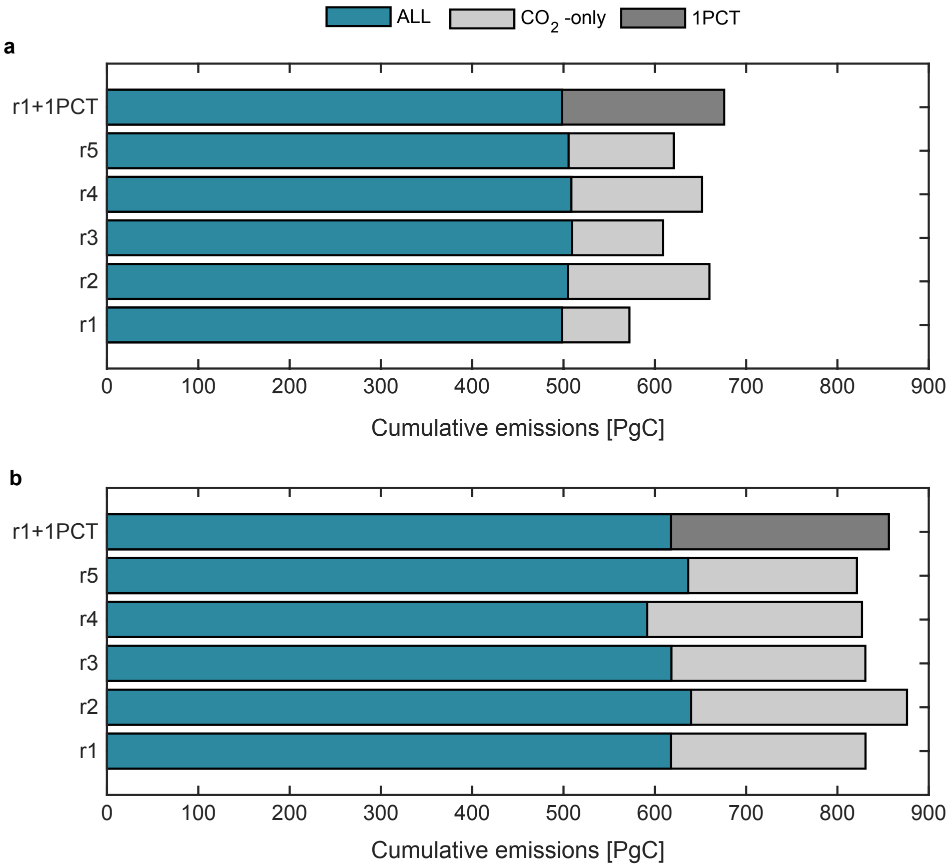


Figure 21. Carbon budgets consistent with not exceeding 1.5°C (panel a) and 2.0°C (panel b) for CanESM2.Comparison of carbon budgets calculated based on 1PCTCO2 simulations (dark grey) with CO_2-only runs (based on RCP 8.5 CO_2 forcing; light grey), and fully forced RCP 8.5 simulations (ALL-forcing; teal) for CanESM2.

Figure 20 and Figure 21 demonstrate that idealized 1PCTCO2 simulations, are a good approximation of the CO_2-only simulations for determining CO_2-only carbon budgets consistent with not exceeding 1.5 °C and 2.0 °C warming thresholds due to CO_2 forcing alone. This approximation allows us to extend the analysis to other comprehensive CMIP5 models using 1PCTCO2 simulations to estimate the CO_2-attributable warming for a given level of atmospheric CO_2 concentration, and compare it with the ALL-forcing response from the RCP 8.5 scenario. Based on this inference, CO_2-only carbon budgets consistent with not exceeding the 1.5 °C and 2.0 °C warming thresholds were calculated for the eleven comprehensive Earth System Models (Figure 22) from the respective 1PCTCO2 simulations.

Cumulative carbon emissions (*CE*) have been calculated from the monthly mean output from the 1PCTCO2 increase simulations, historical, and future RCP 8.5 prescribed CO_2 simulations for the eleven CMIP5 Earth system models that had the data available (calculations explained in Section 3.3.2). Carbon budgets consistent with not exceeding 1.5 °C and 2.0 °C warming are presented in Figure 22. The results vary widely between different models, due to their different representations of physical climate components, and carbon cycle processes. In particular, the differences in carbon cycle are dominated by different representation of terrestrial carbon cycle between the models (Arora et al., 2013; Friedlingstein et al., 2014b). The wide range of responses shown in Figure 22 is discussed in Section 3.4.3.

The results for individual CMIP5 models (presented in Figure 22) are then aggregated into cumulative frequency distribution of carbon budgets consistent with staying below a given warming threshold (according to the weighting scheme calculations explained in Section 3.3.3), and shown in Figure 23, with quantitative details of the distributions reported in Table 1. (These cumulative frequency distributions are discrete, to be directly comparable with the numbers reported in IPCC AR SYR, 2013; Table 1). HadGEM2 model seems to be more sensitive to non-CO_2 forcings such as aerosols (higher than mean effective radiative forcing from aerosols during historical period, as in Rotstayn et al., 2015). Hence, it is likely that at the time of 1.5 °C warming it is still influenced by aerosol forcing (contributing less warming), resulting in its CO_2-only carbon budget being actually lower than ALL-forcing budget (Figure 22). However, at the time when the 2.0 °C threshold is reached, the CO_2-only budget is higher than ALL-forcing budget, as expected and evident in all other models, because aerosol forcing has less of a contributory effect at a later time when 2.0 °C temperature target is reached.

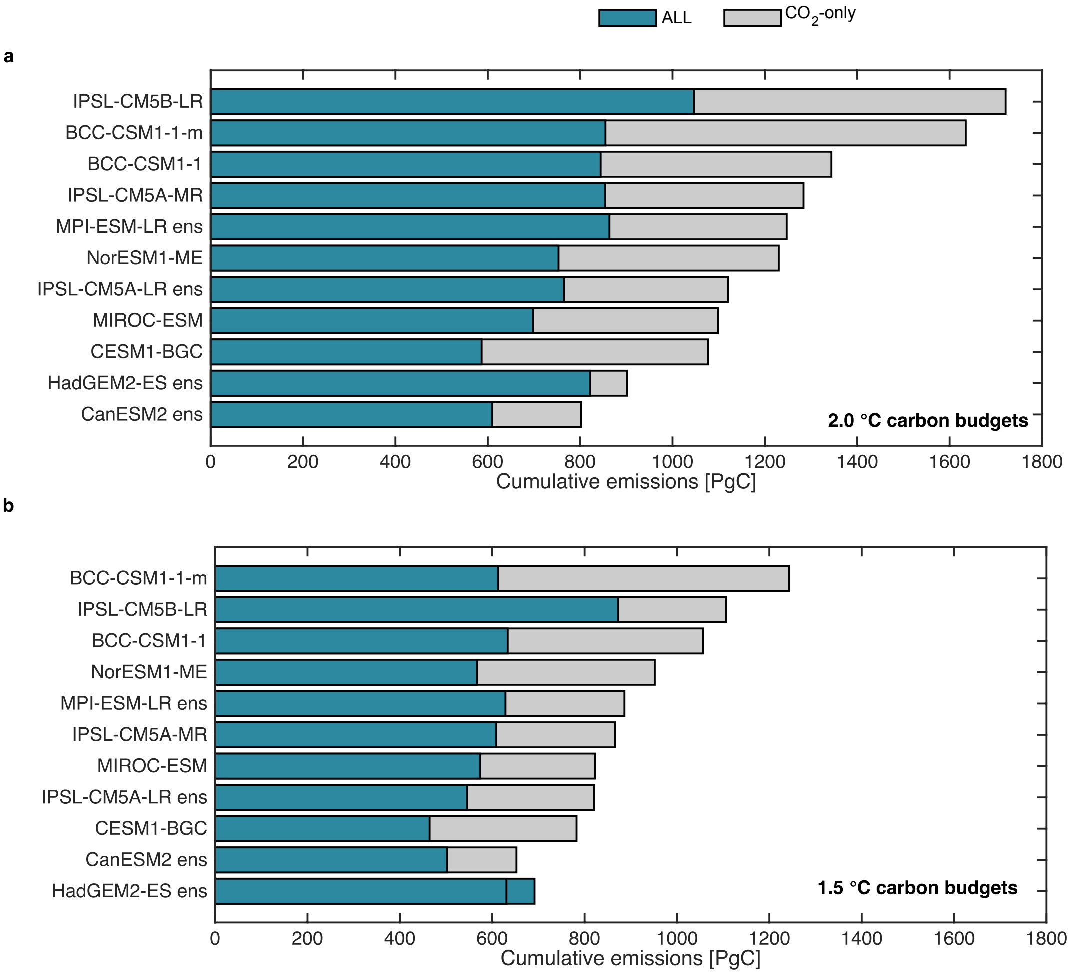


Figure 22. Cumulative carbon budgets consistent with not exceeding 1.5°C (panel a) and 2.0°C (panel b) warming due to CO_2-only forcing (grey bars) and fully forced RCP 8.5 simulation that includes non-CO_2 forcing (‘ALL’, teal bars). Note different order of models on both panels (both panels were sorted in an ascending order of CO_2-only carbon budgets).

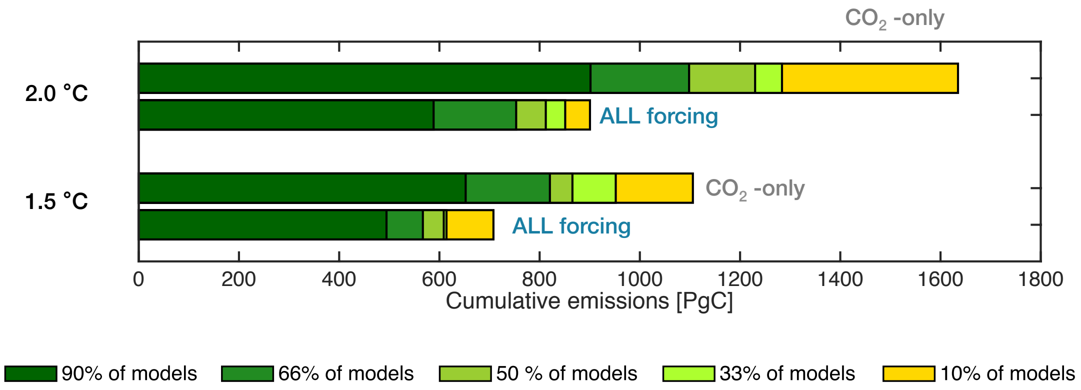


Figure 23. Cumulative frequency distribution of carbon budgets consistent with staying below 1.5 °C and 2.0 °C global mean warming relative to 1861-1880, based on the eleven CMIP5 models for RCP 8.5 scenario. Top bars for each level of peak warming indicate carbon budgets based on CO$_2$-only forcing from 1PCTCO2 simulations. Bottom bars indicate carbon budgets based on the RCP 8.5 simulation that includes all forcings (‘ALL’). Respective model weights for the distributions have been calculated as in Gillett, 2015, and further explained in Section 3.3.3.

Probability of not exceeding the temperature threshold	CO_2-only TCRE-based (IPCC)	CO_2-only direct (1PCTCO2)	ALL forcings (IPCC)	ALL forcings (11 CMIP5)
2.0°C				
>33%	1570	1284	900	851
>50%	1214	1230	820	812
>66%	1000	1098	790	753
1.5°C				
>33%	-	951	-	614
>50%	-	865	-	609
>66%	-	820	-	567

Table 1. IPCC CO_2-only carbon budgets for not exceeding the 1.5 °C and 2.0°C temperature thresholds (inferred from model-based TCRE and observations), compared with CO_2-only carbon budgets from 1PCTCO2 simulations (based on eleven CMIP5 models), and fully forced simulations (ALL) based on RCP 8.5 scenario. Carbon budgets are reported in PgC, since 1861-1880 period. The difference in ALL-forcing estimates (ALL) between the IPCC estimates and the selected 11 CMIP5 models arises from a slightly different set of models used and multiple ensemble members used in this study.

3.4.3. Differences in ranges between CO_2-only and ALL-forcing carbon budgets

Carbon budgets consistent with not exceeding the 2.0 °C warming due to CO_2-forcing alone, calculated from the 1PCTCO2 simulations (Figure 23, upper bars; Table 1), span a substantially narrower range of 186 PgC (between 33% and 66% probability of not exceeding that temperature target), compared with the range width of 570 PgC (between 33% and 66% probability) span by carbon budgets for CO_2-only forcing from the Fifth IPCC Assessment Report (Table 1), which were inferred from the model-based transient climate system response to cumulative carbon emissions (TCRE) and observations (Gillett et al., 2013; IPCC AR5, 2013).

Since the non-CO_2 forcings have a net warming effect in RCP 8.5 scenario, the median carbon budgets consistent with not exceeding a particular warming threshold (>50% probability of not exceeding the temperature target) are hence lower by 257 PgC and 418 PgC for not exceeding the 1.5°C and 2.0°C temperature targets, respectively (Figure 23; Table 1). The carbon budgets from the simulations that include both CO_2 and non-CO_2 forcings (ALL-forcing) both from the IPCC, and from the selected 11 CMIP5 models (which had data available for both ALL-forcing and 1PCTCO2 simulations), span a much narrower range (of 120 PgC and 98 PgC, respectively; between 33% and 66% probabilities), compared with the range spanned by the CO_2-only carbon budgets (Figure 23; Table 1). The potential factors contributing to the differences between CO_2-only and ALL-forcing carbon budgets are explained in the following Section 3.4.4.

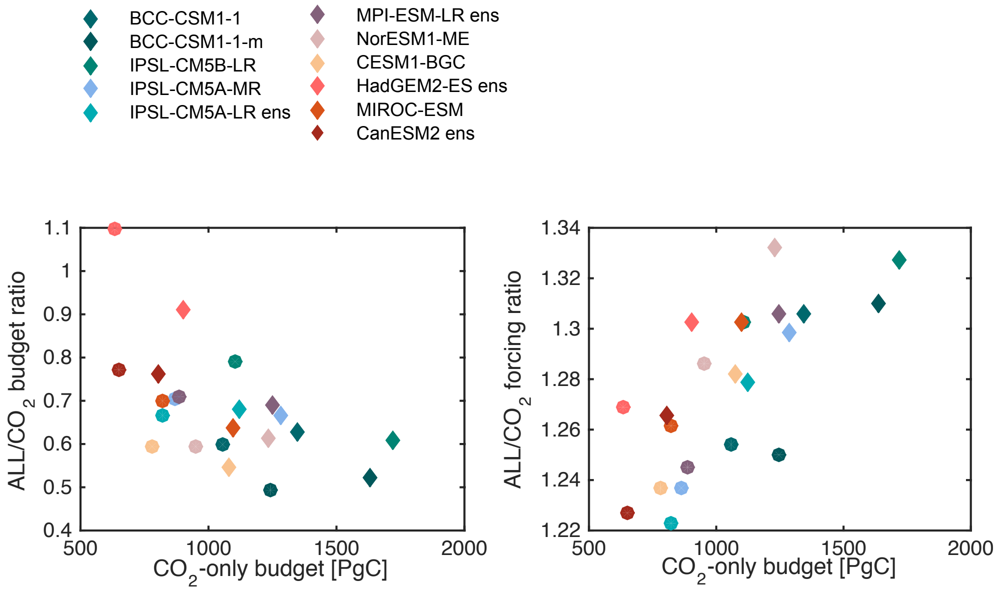
3.4.4. Non-CO_2 forcings and equilibrium climate sensitivity

To further explore the factors contributing to the differences in the wide range of CO_2-only carbon budgets, and a much narrower range of carbon budgets from ALL-forcing simulations, the individual differences between CMIP5 models for CO_2-only carbon budgets (from 1PCTCO2 simulations; Figure 22 gray bars) and ALL-forcing carbon budgets (Figure 22, teal bars), based on the RCP 8.5 scenario, were explored. The models with high equilibrium climate sensitivity (ECS; Section 1.1) (e.g. CanESM2, HadGEM2-ES, MIROC-ESM) have much lower CO_2-only carbon budgets compared to the models with low ECS (e.g. BCC-CSM, BCC-CSM-m, and IPSL-CM5A/B models), while their respective ALL-forcing carbon budgets are not substantially different from the ALL-forcing carbon budgets for the remaining CMIP5 models (Figure 22).

There is a correlation between the ratio of the ALL-forcing and CO_2-only carbon budgets ratio (calculation explained in Section 3.3.2) with respect to the CO_2-only carbon budgets size for both 1.5 °C and 2.0 °C temperature thresholds, shown in Figure 24, with the correlation being more evident for the 2.0°C carbon budgets. Models with high ECS, and hence lower CO_2-only carbon budgets (as they warm faster, reaching relatively low amounts of total carbon emitted in a CO_2-only simulation for a given temperature threshold), tend to have the carbon budgets ratio (ALL-forcing carbon budget /CO_2-only carbon budget; Section 3.3.2; Figure 24) lower and closer to 1, compared to models with low ECS (and thus higher CO_2-only carbon budgets), implying that the models with high ECS are less impacted by the non-CO_2 forcing when calculating their ALL-forcing carbon budgets. Since there may be greater variance in aerosol forcing at the time when 1.5 °C carbon budgets are reached (compared to the time when 2.0 °C carbon budgets are reached), and since the aerosol forcing is not correlated with climate sensitivity (Forster et al., 2014), this effectively is adding noise to the results, and weakening the correlation for 1.5 °C budgets, compared to a stronger correlation evident for 2.0 °C budgets, when the effects from aerosol forcing diminish (Figure 24).

There is no physical reason why models that are more sensitive to CO_2 forcing (i.e. high ECS models) should be less sensitive to non-CO_2 forcing. As shown in Figure 17, the ratio of total radiative forcing to CO_2-only radiative forcing is increasing in RCP 8.5 at the time of exceedance of 1.5 °C and 2.0 °C thresholds, and the ratio of the temperature response to ALL-forcing versus CO_2-only forcing is correspondingly increasing (Figure 20). Hence, models that warm more strongly, with a high ECS and low CO_2-only budgets, reach 1.5 °C and 2.0 °C when the non-CO_2 forcing is low, whereas models that warm slower, with low ECS and high CO_2-only budgets, reach 1.5 °C and 2.0 °C later when the non-CO_2 forcing is higher, narrowing the overall spread in ALL-forcing carbon budgets, compared to CO_2-only carbon budgets. Therefore, the reduced range of ALL-forcing carbon budgets results in part from the forcing history in RCP 8.5 scenario, and is not representative of the full spread of carbon budgets range (as shown by the CO_2-only simulations; Figure 23).

An alternative hypothesis suggests that models that warm more strongly (high ECS) could be indirectly tuned to have a lower response to non-CO_2 forcing, or a higher response to negative aerosol forcing, in order to simulate the historical warming correctly. However, a lack of significant correlation between adjusted forcing and model equilibrium climate sensitivity (Forster et al., 2013), and a large spread in the model temperature responses at present warming (Forster et al., 2013), indicates no evidence regarding adjusting of model forcings to produce observed trends.



◆ 2.0 °C correlation= 0.65

● 1.5 °C correlation = 0.62

◆ 2.0 °C correlation= 0.67

● 1.5 °C correlation= 0.38

Figure 24. Correlation between fully forced and CO$_2$-only carbon budgets with CO$_2$-only carbon budgets (panel a), and between the fully forced and CO-$_2$ only forcing ratio (as in RCP 8.5) and CO$_2$-only carbon budgets (panel b), for 2.0 °C (diamonds) and 1.5 °C (circles). Models with high ECS values are shown in red/orange colours, while models with lower ECS values are in blue and green. Diamonds are for 2.0 °C carbon budgets, circles are for 1.5 °C carbon budgets. The correlations for each panel and each temperature target are listed below.

3.4.5. Seperating reductions in carbon budgets into components due to the climate warming effect, and carbon cycle feedbacks with land use change effects

Non-CO_2 greenhouse gases have a net warming effect, thereby reducing carbon budgets consistent with not exceeding a given temperature threshold. It is typically assumed that the effect of the non-CO_2 forcings on cumulative carbon budgets is simply to increase the warming in a given year, but these non-CO_2 forcings are also expected to reduce the carbon uptake by terrestrial and marine carbon sinks through their additional net-warming effects, as shown in recent studies using an Earth system model of intermediate complexity – the UVic ESCM (Gillett & Matthews, 2010; MacDougall et al., 2015; MacDougall & Knutti, 2016).

These indirect effects of non-CO_2 forcing on carbon budgets can be quantified by comparing warming and diagnosed cumulative carbon emissions in prescribed-concentration RCP 8.5 simulations of CanESM2 which include land use changes, with that in a similar set of simulations in which only CO_2 varies and with no changes in land use. Land use change emissions in RCP 8.5 simulations were calculated directly from CanESM2 simulations with specified land use change and prescribed preindustrial CO_2, and were added to diagnosed fossil fuel emissions from the RCP 8.5 simulations. Since the RCP 8.5 simulations include both land use change and other non-CO_2 forcings, effects of land use change on land carbon uptake could not be separated from effects of other non-CO_2 forcings on land carbon uptake, therefore they are treated as a joint effect (see also Section 3.3.2). The CO_2-only simulation does not include land use change. In order to separate the effects from carbon cycle feedbacks alone, an additional ALL-forcing simulation with no land use change would be needed, which was not available. Further uncertainties regarding land use change are described in Section 3.4.6.

The reductions in CO_2-carbon budgets due to the effects of non-CO_2 forcing can be separated to a combination of the direct climate warming effects (γ), and the combined effects of the land use change and the carbon cycle responses to additional warming (β), illustrated in Figure 25.

The direct climate warming effect

The warming caused by non-CO_2 forcings is equal to the difference in temperature in the ALL-forcing and CO_2-only simulation in the year in which the ALL-forcing simulation exceeds the threshold, or equivalently the warming simulated in the CO_2-only simulation between the years in which the ALL-forcing simulations meets the threshold and the year in which the CO_2-only simulation meets the threshold (as in MacDougall et al., 2015). The cumulative carbon emissions which would cause this much warming are hence the difference in cumulative emissions in the CO_2-only simulation between the year in which ALL-forcing meets the threshold and the year in which CO_2-only meets the threshold (Figure 25, red arrow). Therefore, the reduction in in carbon budgets due to the climate warming effect (ΔCE_{Clim}) can be then expressed by:

$$\Delta CE_{Clim} = CE_{CO_2}(t_{ALL}) - CE_{CO_2}(t_{CO_2}) \tag{3.10}$$

where CE_{CO_2} stands for the cumulative carbon emissions in the CO_2-only simulation; t_{ALL} is the year before the ALL-forcings simulation reaches the given temperature target and $t_{CO_2}$is the year before the CO_2-only simulation reaches the given temperature target. In the t_{ALL}, when the ALL-forcings simulation reaches the given temperature target, the CO_2-attributable warming can be found by examining the warming in the CO_2-only simulation in the same year. The difference in the carbon budgets consistent with 2°C warming due to the climate warming effect can be then calculated as expressed in Eq. 3.10.

The effects due to the carbon cycle feedbacks and land use change

The combined carbon cycle feedback and land use change effect (ΔCE_{Carb}) can be quantified by taking the difference between the cumulative carbon emissions in the ALL-forcing and CO_2-only simulation in the year in which ALL-forcing simulation reaches the temperature target (t_{ALL}), shown in Figure 25 by the green arrow. That time, t_{ALL}, directly represents the effect of non-CO_2 forcings on the carbon emissions budget at the time of ALL-forcing threshold exceedance, which is more relevant to policy makers, who are primarily concerned with carbon budgets that take into account ALL-forcing, rather than CO_2-only forcing. The reduction in carbon budgets due to carbon cycle feedbacks and land use change can be then expressed by:

$$\Delta CE_{Carb} = CE_{ALL}(t_{ALL}) - CE_{CO_2}(t_{ALL}) \tag{3.11}$$

where CE_{ALL} stands for the cumulative carbon emissions in the ALL-forcing simulation, and other variables are defined above.

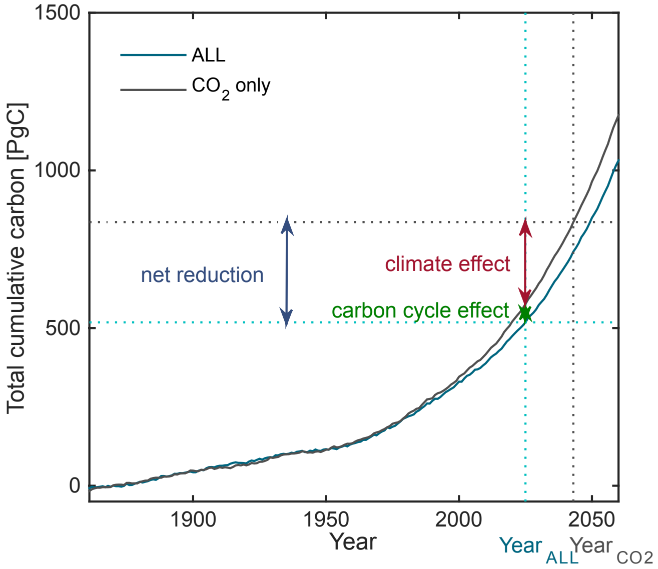


Figure 25. Separating reductions in carbon budgets consistent with 2°C warming due to the climate warming effect, and due to the carbon cycle feedbacks with land use change, in CanESM2. Red arrow represents carbon budget reductions due to the direct warming effect, green arrow represents reductions in carbon budget due to the net carbon cycle effect that includes carbon cycle feedbacks and land use change, and blue arrow represent a net change in carbon budget (difference between red and green bars; see Methods). These arrows correspond to respective bars in Figure 26 (top three bars).

Following the method described above, the indirect effects of non-CO$_2$ forcing on carbon cycle are quantified by comparing warming and diagnosed cumulative carbon emissions in prescribed-concentration RCP 8.5 simulations of CanESM2, with that in a similar set of simulations in which only CO$_2$ varies. Figure 26 illustrates the resulting reductions in carbon budgets consistent with 1.5 ºC and 2.0 ºC temperature targets separated to the climate warming effect (shown in red), and the carbon cycle feedbacks with land use change effects (shown in green). The land use change effect could not be separated from the carbon cycle feedbacks (see also Section §3.4.6). The net resulting effect, indicated by blue bars (Figure 26), represents the reduction in 1.5 °C and 2.0 °C carbon budgets due to non-CO_2 forcings.

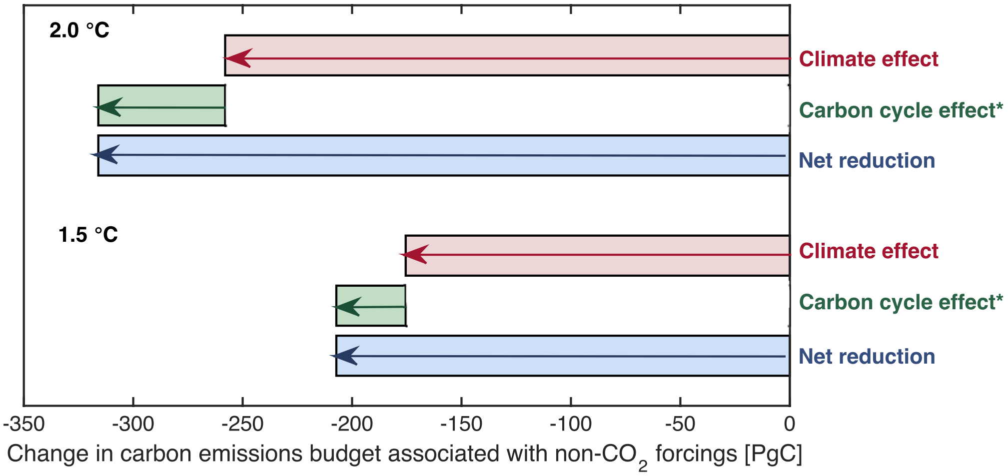


Figure 26. Separation of the effects of non-CO_2 forcings on 1.5 °C and 2.0 °C carbon budgets in CanESM2.
The climate effect (represented by red bars) acts in the opposite direction than the combined effect of carbon cycle feedbacks with land use change (blue bars), still resulting in a net reduction in carbon budget (green bars).
*Carbon cycle effects include land use change, which could not be seperated from the sole effect of non-CO_2 forcings on carbon cycle feedbacks, as explained in text.

Since the representation of terrestrial carbon processes varies between different CMIP5 models (Arora et al., 2013; Friedlingstein et al., 2014b), these responses based on one model only should be treated with caution. Nevertheless, the non-CO_2 forcings primarily affect the climate warming, and their effect on carbon cycle feedbacks and carbon sinks is secondary, which is consistent with MacDougall et al., 2015, who also reported reductions in carbon budgets due to non-CO_2 forcings on carbon cycle feedbacks to be less than the reductions due to the climate warming, using an Earth system model of intermediate complexity (MacDougall et al., 2016). Greater reductions in the CO_2-only carbon budgets due to the climate warming effect are needed for higher temperature targets, as the net warming effect of non-CO_2 greenhouse gases on carbon budgets becomes stronger at a later time (when higher temperature targets occur), due to declining aerosol forcing (Figure 17).

3.4.6. Land use change uncertainties

The Canadian Earth System Model (CanESM2), similarly to the other CMIP5 Earth system models used in this study, includes a coupled carbon cycle. The ALL-forcing RCP 8.5 simulation includes land use changes. However, land use change emissions cannot be diagnosed directly from the model output (Section 3.3.2). Therefore, an estimate of the cumulative land use change emissions from the prescribed land-use change RCP 8.5 scenario (from the RCP database, van Vuuren et al., 2011) has been added to the total cumulative emissions, in order to account for the carbon emissions from land use change that are simulated by the models forced with the RCP 8.5 scenario, except for BCC-CSM 1.1 and BCC-CSM 1.1-m models in which LUC is not prescribed, diagnose land use change emissions jointly with fossil fuel emissions. The land-use change emissions used in design of RCP pathways are based on historical estimates of shifting cultivation, crop, pasture and wood harvest, interpolated into future based on integrated assessment models implementations of the RCP pathways (Hurtt et al., 2011).

In order to assess the sole effect of land-use change a better estimate of land use change emissions in each model would be needed, instead of the approximation described above. The net land use change emissions would be more accurately estimated by taking a difference between the fully coupled RCP simulations with and without land use change (Arora et al., 2011; Arora and Boer, 2010). However, ALL-forcing simulations without land use change were not available for any of the models.

Land use change has multiple impacts on the carbon exchange between the land and atmosphere, as well as more indirect (non-carbon) effects, which cannot be diagnosed directly from the model output. Considering one example of land use change in a form of deforestation, the following direct and indirect effects would need to be considered, such as:

- immediate release of carbon to the atmosphere (from burning some of deforested vegetation)
- reduced future carbon uptake capacity (the clear cut areas when replaced by croplands will not respond to increasing CO_2 as much as the original vegetation,

since crops are harvested, thereby not allowing above ground biomass to increase in size)

- tilling of the land areas accelerates soil carbon decomposition (due to mixing up of the soil layers), thereby reducing soil carbon amounts

In addition the following non-carbon effects play a role:

- changes in surface roughness affect evapotranspiration rates
- changes in surface coverage (from forest to crop land, for example), affect the surface albedo, that in turn have impacts on surface energy balance, and hence, temperature changes

The net effect of these factors is difficult to estimate. Large uncertainties remain both in physical and biogeochemical effects of land use change. Differences in processes represented by ESMs (such as secondary forest regrowth, included by some but not all models), also pose a difficulty for model Intercomparison (Pongratz et al., 2014), as the RCP estimate of land use change may include different terms than those which are internally calculated by ESMs .

3.5. Discussion and Conclusions

Permafrost carbon cycle feedbacks were not included in those CMIP5 models, and could lead to additional warming (estimated to range between 0.13 and 0.27 °C by year 2100 in RCP 8.5 scenario, Schuur et al., 2015), potentially further reducing carbon budgets consistent with not exceeding a given temperature threshold. However, the effects of additional warming from permafrost carbon feedbacks would likely be negligible at the time of threshold exceedance of 1.5 °C and 2.0 °C carbon budgets, which would be reached much sooner than year 2100. While MacDougall et al., 2015 report reductions in the 2.0 °C carbon budget even as high as 85 PgC due to permafrost carbon cycle feedbacks, those feedbacks in that particular model are on the high end of the inter-model range (MacDougall et al., 2015).

The results presented here are sensitive to uncertain future scenarios of non-CO_2 greenhouse gases and aerosol forcing (Rogelj et al., 2015b,c). If future non-CO_2 forcings were substantially different from RCP scenarios, their net warming effect could have an even larger impact on the resulting carbon budget reductions. However, there would not be substantial differences in carbon budgets consistent with different levels of warming calculated from different RCP scenarios, as CO_2 is the dominant forcing, and the ratio of CO_2 to total forcing is approximately constant across the RCP scenarios. Such conclusions are supported by a recent study of MacDougall et al., 2015, who compared carbon budgets for different RCP scenarios using a simpler model. Emissions from non-CO_2 greenhouse gases are partly linked to CO_2 emissions, through their economic and technological factors (Rogelj et al., 2015a,b). Strong CO_2 mitigation would likely be accompanied by mitigation of non-CO_2 greenhouse gases, and therefore, their relatively smaller contribution to overall warming (Rogelj et al., 2014). Due to large uncertainty of future non-CO_2 emission trajectories, recent studies (e.g. Clarke et al., 2014) make use of CO_2-equivalent pathways (based on global warming potentials of non-CO_2 agents), to allow for scenario inter-comparison.

An alternative approach to cumulative emission carbon budgets calculated from CO_2-only simulations, and compared with ALL-forcing simulations, could be to discuss CO_2-equivalent carbon budgets, which account for cumulative non-CO_2 emissions, converted to the their CO_2-equivalents. However, the non-CO_2 forcing time scales are uncertain (i.e. different non-CO_2 species have different lifetimes, which are much shorter than the lifetime of CO_2). To address the issue of different lifetimes between the forcers, CO_2 equivalent targets would need to be separated between cumulative pollutants, and short-lived greenhouse gases (Allen et al., 2016).

Some methane emissions are directly linked to CO_2 emissions (e.g. release of methane from fossil fuel extraction), and therefore the mitigation of methane and CO_2 emissions would be somewhat linked, however, this coupling is relatively weak (Rogelj et al., 2014). Overall, both: CO_2 and short-lived climate forcers (i.e. non-CO_2 greenhouse gases) become smaller in scenarios that keep warming to below 2.0 °C above the preindustrial level (Rogelj et al., 2014). The non-CO_2 forcing at the time when 1.5 °C and 2.0 °C budgets are reached may be different from non-CO_2 forcing at climate stabilization, likely smaller at the time of stabilization, due to prior mitigation of both CO_2 and non-CO_2 emissions, but still highly scenario-depended.

Since, on average, CMIP5 models warm more than observations (IPCC AR5, 2013; Forster et al., 2013; Tokarska & Gillett, in review), the carbon budget estimates provided here are somewhat conservative. Observationally-constraining the model responses (as explained in Chapter 5), and changing the base period to the recent decade (Millar et al., 2017; Tokarska & Gillett, in review) could lead to more accurate estimates of carbon budgets consistent with different temperature thresholds.

Carbon budgets presented here are threshold exceedance budgets (Rogelj et al., 2016; Section 1.4), that are based on scenarios that exceed a given temperature threshold in the subsequent years. The threshold exceedance budgets based on RCP simulations that include both CO_2 and non-CO_2-forcing, assume that non-CO_2 forcing will evolve as a function of cumulative emissions, as it does in the given RCP scenario. However, carbon budgets from ALL forcing simulations include different levels of non-CO_2 forcing, depending at what time the budget was calculated (i.e. high ECS models reach the warming threshold sooner than models that warm slower, which corresponds to a different level of non-CO_2 forcing, and results in artificially narrowing down the distribution of ALL-forcing budgets, compared with the CO_2-only budget based on RCP 8.5 simulations.

Previous studies (IPCC, 2013; Rogelj et al., 2016) primarily focus on carbon budgets due to CO_2-attributable warming alone, to avoid uncertainties associated with additional non-CO_2 forcings (Rogelj et al., 2016). Inclusion of non-CO_2 forcings in carbon budgets estimates has a net-warming effect in RCP 8.5 scenario, leading to carbon budget reductions compared with the CO_2-only simulations, by 257 PgC and 418 PgC, for 1.5°C and 2.0°C temperature targets, respectively, and results in a narrower range of the ALL-forcing carbon budgets spread (based on results from eleven CMIP5 models). This study confirmed that CO_2-only carbon budgets derived directly from 1PCTCO2 simulations are a good approximation of the CO_2-only RCP simulations (based on CanESM2 simulations), and result in a narrower range than the CO_2-only carbon budgets inferred from TCRE and observations.

The factors contributing to narrowing down of the spread of the range of ALL-forcing carbon budgets compared to CO_2-only carbon budgets partially arise from the forcing history in the RCP 8.5 scenario. Models that warm strongly, with ECS and low

CO_2-only carbon budgets, reach a given temperature target when non-CO_2 forcings are still low, and conversely, models that warm more slowly (low ECS and high CO_2-only carbon budgets), reach the warming targets when non-CO_2 forcings are higher. As a result, inclusion of non-CO_2 forcings (resulting in forcing history in RCP 8.5 scenario), and use of threshold exceedance budgets, artificially narrows the spread of the range of ALL-forcing carbon budgets, compared to CO_2-only carbon budgets, and may be a feature of RCP scenarios, thereby, making carbon budget reductions sensitive to non-CO_2 emission trajectories. Hence, the range of ALL-forcing carbon budgets is not representative of the full spread of carbon budgets range.

While non-CO_2 forcings affect the climate warming, their effect on carbon cycle feedbacks and carbon sinks is secondary. Since carbon emissions budgets are expected to play an increasingly important role in international climate policy, understanding the influence of non-CO_2 forcings on these budgets and their uncertainties is critical to taking accurate measure that aim to reach global mean temperature targets.

Chapter 4. Project III: Observationally-constraining cumulative carbon budgets consistent with 1.5°C warming

This chapter is based on the contents of the paper:

K.B. Tokarska and N.P. Gillett. (2017). Cumulative carbon emissions budgets consistent with 1.5°C warming. (in review)

4.1. Introduction and Motivation

After the United Nations Climate Change Conference in Paris (COP 21) in December 2015, 196 countries signed the Paris Agreement that commits the ratifying parties to 'pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change' (UNFCC, 2015; Article 2). As a result of actions arising from the Paris Agreement, COP 21 invited the IPCC to 'provide a special report in 2018 on the impacts of global warming of 1.5°C above preindustrial levels, and related global greenhouse gas emission pathways', and therefore, there is an urgent need for accurate estimates of cumulative carbon budgets consistent with the 1.5°C peak warming.

The IPCC Fifth Assessment Report (IPCC AR5) provides estimates of cumulative carbon budgets consistent with four levels of peak warming (1.5°C, 2.0 °C, 2.0 °C and 3.0 °C), based on simulations from comprehensive Earth System Models (from the CMIP5 Model Intercomparison Project) for the RCP 8.5 scenario, which represents a business-as-usual scenario of high levels of radiative forcing (Figure 16; Figure 27). The black vertical line at 515 PgC in Figure 27 indicates the observed historical cumulative carbon emitted for the period 1870-2011, as assessed by IPCC AR5, 2013. However, based on CMIP5 model responses to the RCP 8.5 scenario, Figure 27 shows that the lowest simulated carbon budgets consistent with the 1.5°C peak of approximately only 500 PgC had already been exceeded in 2011, as indicated by the 90th percentile of the CMIP5 model responses. However, observed warming in 2011 relative to 1861-1880 was below 1.0°C (IPCC, 2013; TFE Figure 1c) and has a median value of 0.85 °C (ranging from 0.65°C to 1.06°C), over the period 1880–2012 (IPCC, 2013).

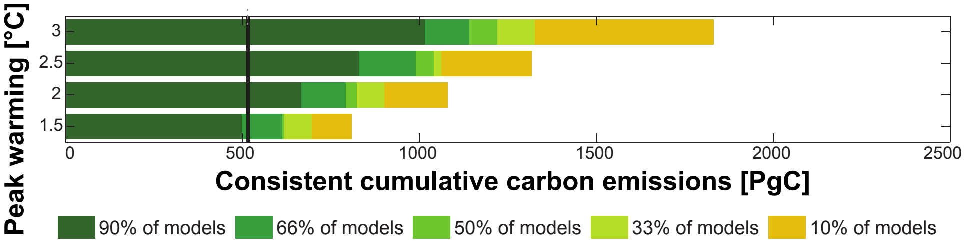


Figure 27. Cumulative CO_2 emissions since year 1870, consistent with four peak global temperature limits, based on the RCP 8.5 scenario (IPCC AR5, 2013, TFE.8, Figure 1c). Note: These cumulative carbon emissions for different levels of peak warming were calculated from Figure 16.

Comparing the multi-model mean climate model responses (Figure 28, black line) for a historical period (1870-2011) with observed historical values (Figure 28, pink line), the model responses tend to be above the historically observed curve (Figure 28). It is apparent that most CMIP5 models warm more than observations at the current levels of cumulative carbon emitted. Hence, the carbon budgets consistent with different levels of peak warming based on CMIP5 model responses tend to be conservative and may underestimate the total amount of carbon that could be emitted while remaining below a given level of the peak warming.

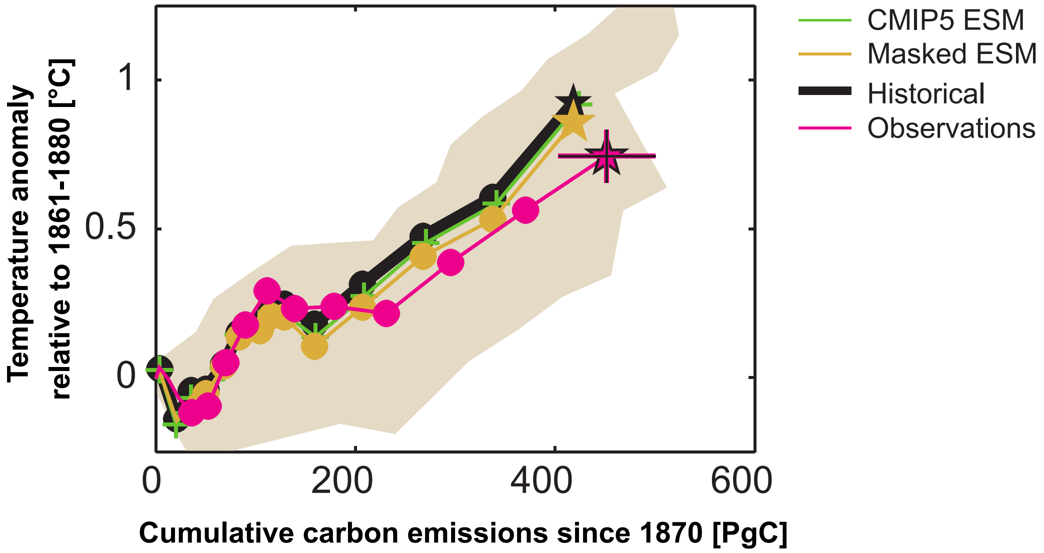


Figure 28. Comparing historical model results with observations (IPCC AR5, 2013, TFE.8, Figure 1b). The black line indicates the multi-model mean response for all the models considered (CMIP5 ESMs and EMICs), while the pink line indicates the observations. The masked ESM (yellow line) represents ESM responses corrected for HadCRUT4's incomplete geographical coverage over time (as in IPCC AR5, 2013, TFE.8, Figure 1b).

4.2. Research Questions

The key research questions that his project addresses are:

- Given that CMIP5 models warm on average more than observations as a function of cumulative emissions, can the model responses be observationally-constrained to obtain more accurate projections of the carbon budget consistent with the 1.5 °C carbon budget (and carbon budgets consistent with higher levels or warming)?
- Is the 1.5 °C carbon budget attainable, given that some models indicate that it has already been exceeded?
- How much more carbon can be emitted on a global scale before the 1.5 °C climate target is reached?

4.3. Methods

4.3.1. Models and scenarios

This study makes use of 16 comprehensive Earth system models (ESMs) from the Fifth Coupled Climate Model Intercomparison Project (Taylor et al., 2012) (CMIP5; listed in Table 2), driven by historical and future scenarios: Representative Concentration Pathways 4.5 and 8.5 (van Vuuren et al, 2011), which reach a radiative forcing levels of 4.5 W/m^2 and 8.5 W/m^2 by year 2100 respectively. The RCP 2.6 simulations are not included in the analysis, to avoid bias towards models that warm more strongly, because some of the RCP 2.6 simulations do not reach 1.5 °C global warming by 2100.

4.3.2. Temperature calculations and present level of warming

For each CMIP5 model considered, the global mean temperature anomaly for each year was calculated from monthly mean anomalies separately for each of three datasets, using the same coverage and base period as the respective observational temperature data set (HadCRUT4, GISS or NOAA) (Morice et al., 2012; Vose et al., 2012; Hansen et al., 2010; Smith et al., 2008; GISTEMP, 2016). For the observational data sets that start at year 1880, the temperature change between the periods 1880-1899 and 1861-1880 was calculated based on HadCRUT4 values and was added to the respective observational estimates of warming. An equivalent calculation using the same observational masking was performed for the simulated temperature data. A running decadal mean anomaly relative to the 1861-1880 period was calculated for the masked model data sets, to determine the year preceding the year in which a given model reaches the level of warming over the past decade (2006-2015) for each observational dataset separately, where the observed warming for the recent decade (2006-2015), relative to 1861-1880, for each of the observational data sets is: 0.89 °C (HadCRUT4), 0.93 °C (GISS) and 0.84 °C (NOAA).

The model global mean temperature response at 1.5 °C warming (used to calculate 1.5 °C carbon budgets) was obtained from spatially complete model temperature output (without masking) as an anomaly relative to 1861-1880, and with respect to the corresponding year in the pre-industrial control simulation, to remove the effects of any drift.

4.3.3. Cumulative fossil fuel emissions

To avoid uncertainties related to estimates of land use-change, only the fossil-fuel carbon emissions budgets at present warming were compared with an observational estimate of the total amount of fossil-fuel emissions 370.3 PgC ± 20 PgC (Le Quéré et al, 2013), for the period 1870-2011, where year 2011 represents the middle of the recent decade (2006-2015). Uncertainties are reported as $\pm 1\sigma$. Cumulative frequency distributions of emissions budgets (calculations explained in Section 3.3.2) are shown in Figure 23 and Figure 31.

4.3.4. Testing for model inclusion using observational constraints

To observationally-constrain the model responses, the models were screened for consistency with observations of cumulative fossil fuel emissions at observed warming. The consistency test accounted for uncertainties associated with observational uncertainty in temperature, observational uncertainty in cumulative fossil fuel emissions, and uncertainties arising from internal variability in the observations and models. For the i^{th} model, j^{th} observational temperature dataset and k^{th} ensemble member, the cumulative fossil fuel carbon budget at the present warming $\left(F_{T\_obs}\right)_{ijk}$ was estimated from a combination of a historical and RCP 4.5 simulations, since RCP 4.5 was the scenario with the most ensemble members (Figure 2). For models with multiple ensemble members, carbon budgets consistent both with present day warming and with 1.5 °C warming were found not to be significantly different when calculated from the RCP 2.6, RCP 4.5 or RCP 8.5 scenarios, using two-sample t-tests. Since some models only had a single ensemble member available and others had only small ensembles, the simplifying assumption was made that internal variability in F_{T_obs} was equal in all models and in observations. This internal variability reflects internal variability in temperature, and to a lesser extent internal variability in the carbon cycle. To estimate the variance associated with internal variability in the cumulative fossil fuel carbon budgets at the present warming (Eq. 1.3), the sample variance in F_{T_obs} across all ensemble members was calculated for the *i*th model using the *j*th observational dataset, which is denoted as $\sigma^2_{I\,ij}$. The model mean variance associated with internal variability σ_I^2 was then estimated by:

$$\sigma_I^2 = \overline{\left(\frac{N_i}{N_i - 1}\sigma^2_{I\,ij}\right)} \tag{4.1}$$

where N_i is the ensemble size for the *i*th model. The overbar indicates an average across the models and across the three observational data sets (HadCRUT4, NOAA, GISS).

The observational uncertainty variance for the observed cumulative fossil fuel carbon emissions σ_F^2 (400 $[\mathrm{PgC}]^2$) for the period 1870-2010 was calculated from the Global Carbon Project (Le Quéré et al., 2011), and based on the $\pm 1\sigma$ uncertainty range.

The variance in F_{T_obs} associated with observational uncertainty in temperature was estimated from the spread in emissions budgets calculated with the three different temperature data sets, and is denoted as σ_T^2 (Eq. 4.2), where J is the number of observational temperature data sets (J = 3) and $\sigma^2_{T\,ik}$ is the sample variance in cumulative emissions budgets across the three different observational datasets for the *i*th model and *k*th ensemble member, and the overbar represents an average across models and ensemble members.

$$\sigma_T^2 = \left(\frac{J}{J-1}\right)\overline{\sigma^2_{T\,ik}} \tag{4.2}$$

For the *i* th model the difference *D* is defined as:

$$D_i = \overline{\left(F_{T\_obs}\right)_{ijk}} - F_{Obs} \tag{4.3}$$

where the overbar indicates an average over ensemble members, *k*, and observational temperature datasets, *j*, and F_{Obs}= 360.8 PgC $\pm$ 20 PgC (IPCC AR5, 2013). The difference D_i was divided by an estimate of its standard deviation under the null hypothesis that the simulated and observed cumulative fossil fuel emissions budgets are drawn from the same distribution:

$$x_i = \frac{D_i}{\sqrt{\sigma_F^2 + \sigma_I^2\left(1 + \frac{1}{N_i}\right) + \sigma_T^2}} \tag{4.4}$$

where the term $(1 + \frac{1}{N_i})$ is included to account for internal variability in both the observations and the model. The variances had the following values: σ_F^2=400 $[\mathrm{PgC}]^2$, σ_I^2=524 $[\mathrm{PgC}]^2$, and σ_T^2=317 $[\mathrm{PgC}]^2$, indicating that internal variability is the largest contributor to the standard deviation in D_i. Making the simplifying assumption that x_i is normally distributed under the null hypothesis, the p-value corresponding to x_i for a normal distribution was calculated (using a two-tailed distribution at a significance level of 0.1). A model was considered consistent with the observations if $p(x_i) > 0.1$ (results shown later in Table 2). Further analysis was performed regarding sensitivity of the results to the base period chosen, and sensitivity of the results regarding different significance levels, discussed in Section 4.4.3.

Subsequently, the cumulative carbon budgets consistent with the 1.5°C warming (and other levels of warming) were calculated based only on the models that passed the observationally constrained test. These results were then compared with the carbon budgets derived from all CMIP5 models for all RCP scenarios that reach a given level of peak warming. This method accounts for the uncertainties related to the internal variability of climate models, and uncertainties with observed estimate of the cumulative carbon emissions and observed temperature records.

4.4. Results

4.4.1. Physical climate change results

Global mean temperature and diagnosed cumulative carbon emissions simulated in response to both scenarios (RCP 4.5 and RCP 8.5) are shown in Figure 29. The simulations first reach 1.5 °C global warming, relative to an 1861-1880 base period, between years 2005 and 2054 (Figure 29a). For comparison, observed warming of 0.89 °C for the past decade (2006-2015) relative to 1861-1880 is indicated by dotted lines (Figure 29a).

Total cumulative fossil fuel carbon emissions (Figure 29b) were calculated for models in which land-use change was implemented by summing time-integrated atmosphere-land carbon fluxes, atmosphere-ocean carbon fluxes and the atmospheric carbon anomaly relative to 1861-1880. For the BCC-CSM-1-1-m and BCC-CSM-1-1 models in which land-use changes were not implemented, cumulative fossil fuel carbon emissions were calculated by summing time-integrated atmosphere-land and atmosphere-ocean carbon fluxes with the atmospheric carbon anomaly and subtracting an estimate of cumulative land-use change emissions, as prescribed in the corresponding RCP scenario. Total cumulative carbon emissions (Figure 29c) were calculated by adding an estimate of cumulative land-use change emissions for the corresponding RCP scenario, to the fossil fuel cumulative carbon emissions shown in panel Figure 29b (calculations described earlier in Section 3.3.2). The spread in the cumulative carbon emissions in panels (b) and (c) arises from different representations of carbon cycle processes in the CMIP5 models considered here (Arora et al., 2013; Friedlingstein et al., 2014b). The relationship between warming and cumulative carbon emissions is shown in Figure 29d.

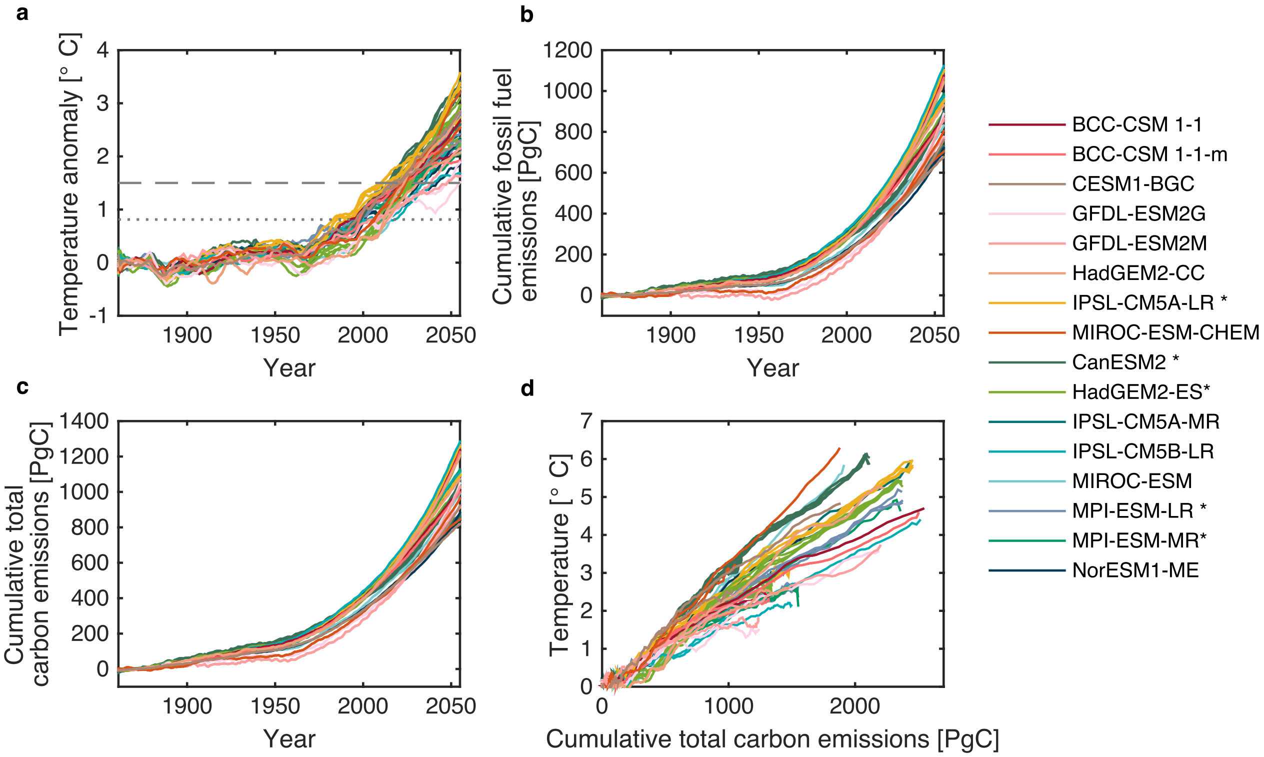


Figure 29. Time series of global mean temperature and cumulative carbon emissions for RCP 4.5 and RCP 8.5 scenarios (a-d), relative to 1861-1880. (a) global mean temperature anomaly (decadal mean); (b) cumulative fossil fuel emissions; (c) cumulative total carbon emissions; (d) temperature change as a function of cumulative total carbon emissions. The dotted line in panel (a) indicates the present warming level (0.89 °C; average between the three observational data sets), and the dashed line indicates the 1.5°C warming threshold. Anomalies are calculated with respect to the corresponding year in the pre-industrial control simulation to remove the effects of any drift.

4.4.2. Consistency test results

Model screening

Figure 30 shows a correlation (*r* = 0.37) between the model cumulative fossil-fuel emissions at present warming (Figure 30, horizontal axis) and the cumulative total carbon emissions consistent with limiting warming to less than 1.5 °C (Figure 30, vertical axis). The fact that this correlation is relatively low likely relates to differing responses to non-CO_2 forcings between models (Forster et al., 2013), since the relative contributions of these forcings, particularly aerosols, differ strongly at present warming and at 1.5 °C warming above the pre-industrial level. Nonetheless, since there is a weak correlation between these quantities, we investigate whether by comparing the simulated cumulative fossil-fuel carbon emissions at present warming (Figure 30, horizontal axis) with the reported cumulative fossil-fuel carbon emissions at present warming (Figure 30, dashed lines), 1.5 °C carbon budgets might be observationally constrained, by screening out models that are inconsistent with observations. This therefore suggests that by comparing the simulated cumulative fossil-fuel carbon emissions at present warming (Figure 30, horizontal axis) with the observed cumulative fossil-fuel carbon emissions at present warming (Figure 30, dashed lines), 1.5 °C carbon budgets might be observationally constrained, by screening out models that are inconsistent with observations. A consistency test was performed (described in Section 4.3.4), which accounts for uncertainties related to the internal variability, uncertainties in the observed estimate of cumulative carbon emissions and observational uncertainties in temperature. The uncertainty in the observed temperature measurements was accounted for in the term σ_T^2 (317 PgC^2), and is smaller than the other uncertainties in the observed cumulative fossil fuel emissions σ_F^2 (400 PgC^2) or the uncertainty associated with internal variability σ_I^2 (524 PgC^2) (Section 4.3.4). This approach is limited by the number of models for which suitable simulations are available, therefore, 10th and 90th percentiles shown in Figure 31 (and subsequent figures) should be interpreted with caution, though the median is likely to be more robust.

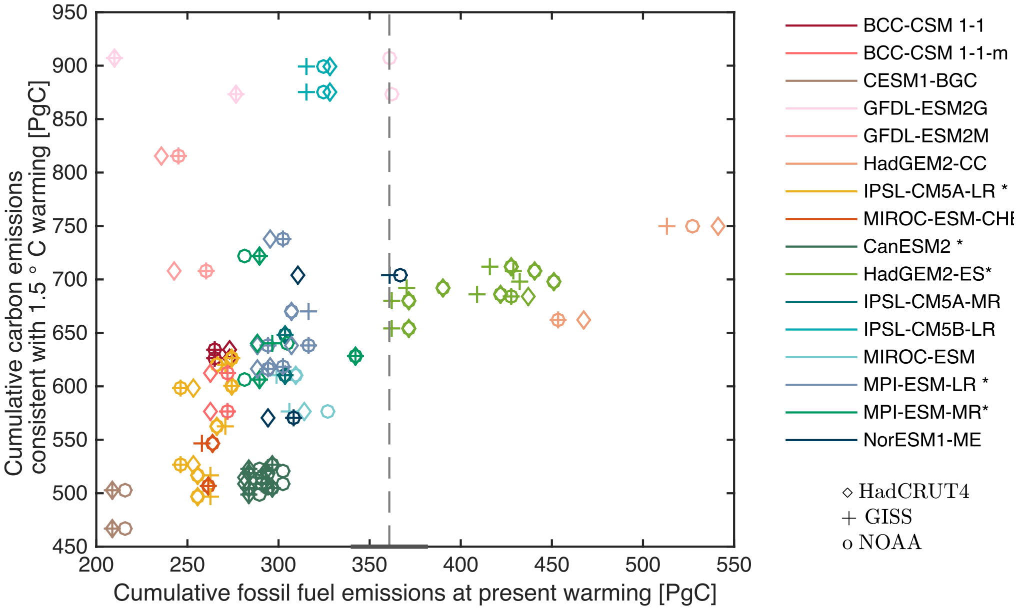


Figure 30. Simulated cumulative fossil-fuel carbon emissions at present warming (horizontal axis), and cumulative total carbon budgets consistent with 1.5 °C warming (vertical axis) for RCP 4.5 and RCP 8.5 scenarios. The dashed line indicates an estimate of the observed historical cumulative fossil fuel emissions for the period 1870-2010 with the median value of 360.8 PgC (Le Quéré et al., 2014), where year 2010 represents the middle of the recent decade (the ± 20 PgC uncertainty of this estimate is indicated by the horizontal black bar). Different symbols (indicated in the legend) represent cumulative emissions budgets calculated using different observational data sets of temperature. Models shown in shades of blue or green passed the consistency test (Section 4.3.4), while models in shades of red and orange failed it.

Eight out of the sixteen models considered here were found to have cumulative carbon emissions at the present level of warming significantly lower than actual emissions, and one model was found to have cumulative carbon emissions significantly higher than actual emissions, for which the consistency test yields a p-value smaller than 0.1 (Table 2). The results do not differ much when the significance level of the consistency test is changed from 0.1 to 0.05 or 0.2 (described in the following section; Figure 34), as most of the models either pass or fail the test at all these three significance levels. Carbon budgets consistent with staying below 1.5 °C warming were calculated based on all model responses (Figure 31; ALL bars), and based only on the models that are consistent with observations (Figure 31; OC bars). In each case, all available ensemble members were used, with ensemble members weighted in such a way that each model had equal weight, in order to avoid a bias towards models with larger ensembles (Gillett, 2015; described earlier in Section 3.3.3, and Section 4.3.4). The bars in Figure 31 represent percentiles of the resulting distributions. The unconstrained carbon budgets for 1.5 °C warming (Figure 31, ALL bars) closely resemble the values reported by the IPCC AR5 (Collins et al., 2013; also shown in Figure 27), and comparison in Table 3), with the differences arising from consideration of multiple ensemble members, inclusion of RCP 4.5 results, and the slightly different sets of models used. The 10th percentile of the unconstrained budgets had already been exceeded in 2015 (Figure 31, top 'ALL' bars and the grey dashed line), suggesting a greater than 10% chance that we are already committed to 1.5 °C warming (unless CO_2 is artificially removed from the atmosphere), but the 10th percentile based on the models consistent with observations has not been exceeded. The median remaining carbon budget consistent with staying below 1.5 °C peak warming, relative to year 2015, is 72 PgC, based on unconstrained responses of all models considered here, and 83 PgC, based on model responses that are consistent with observations, an increase of approximately 15%.

Model name	**OC (2006-2015)**	**OC (2002-2011)**	**OC (1995-2006)**
BCC-CSM 1.1	N	**Y**	**Y**
BCC-CSM 1.1-M	N	Y	**Y**
CanESM2*	**Y**	**Y**	**Y**
CESM-BGC	N	N	**Y**
GFDL-ESM-2G	N	**Y**	**Y**
GFDL-ESM-2M	N	N	**Y**
HadGEM2-CC	N	N	N
HadGEM2-ES*	**Y**	N	N
IPSL-CM5A-LR*	N	**Y**	**Y**
IPSL-CM5A-MR	**Y**	**Y**	**Y**
IPSL-CM5B	**Y**	**Y**	**Y**
MIROC-ESM	**Y**	**Y**	**Y**
MIROC-ESM-CHEM	N	**Y**	**Y**
MPI-ESM-LR*	**Y**	**Y**	**Y**
MPI-ESM-MR*	**Y**	**Y**	**Y**
Nor-ESM1-ME	**Y**	**Y**	**Y**

Table 2. Consistency test results based on a comparison of simulated cumulative fossil fuel emissions at observed warming with that observed, for the three different observational base periods (OC) considered here. ‘Y’ indicates that the given model passed the consistency test based on the observational constraints for the given base period considered (indicated in the top row), at a 0.1 significance level (Section 4.3.4). Conversely, ‘N’ indicates that the model did not pass it. An asterisk indicates models with multiple ensemble members.

4.4.3. Observationally-constrained carbon budgets

Observationally-constrained carbon budgets relative to the recent decade

Following Millar et al., 2017, to reduce the effects of model biases originating from uncertainties in carbon emissions during the historical period, we re-calculated carbon budgets consistent with the 1.5 °C level of global warming relative to a different base period: the recent decade (2006-2015), for both sets of models, which include all available simulations (Figure 31; ALL bars), and observationally-constrained carbon budgets based on models that pass the consistency test (the same subset of models as in the top two panels); (Figure 31, OC bars). Changing the base period to the recent decade has a larger effect of increasing the median carbon budget than observationally constraining the model responses based on the model weighting approach (Figure 31), due to elimination of uncertainties related to historical carbon emissions. Accounting for both effects of changing the base period to the recent decade and considering only models that are consistent with observations, the median remaining carbon budget consistent with staying below 1.5 °C level of peak warming, relative to year 2015, is 240 PgC. Comparing these results with the carbon budgets reported in the IPCC AR5 (compared in Table 3), the remaining carbon budgets reported in this study are nearly four times as large as the remaining IPCC estimate from 2015 (Table 3), and twice as large as the estimate since 2011, therefore indicating using a recent base period in calculating temperature and total amount of carbon emitted significantly increases the remaining amount of carbon that can be emitted to meet a given temperature target.

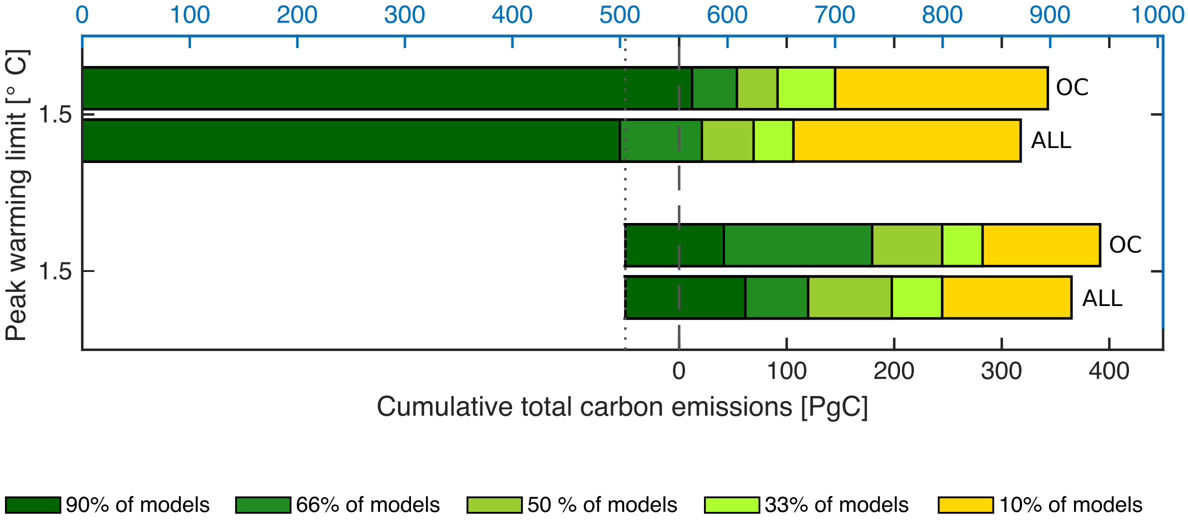


Figure 31. Observationally constrained carbon budgets consistent with 1.5°C warming. Cumulative frequency distribution of carbon budgets consistent with staying below 1.5 °C global warming based on all (unconstrained) CMIP5 models considered here (ALL, lower bars for each pair), and observationally-constrained carbon budgets based on models consistent with observations (OC, upper bars for each pair), for two different base periods: 1861-1880 (top two bars), and 2006-2015 (bottom two bars). The grey dashed line indicates the observational total cumulative carbon emissions for the period 1870-2015, with the median value of 555 PgC (IPCC AR5, 2013), while the dotted line indicates cumulative carbon emissions up to year 2010. The top two bars show carbon budgets relative to 1861-1880 decade (blue axis), in PgC. The bottom two bars show carbon budgets relative to the recent decade 2006-2015, offset by the IPCC estimate of the cumulative carbon emissions up to 2010, which represents the middle of that decade. The lower axis shows carbon budgets relative to year 2015, while the top axis shows budgets relative to 1861-1880. See Section 4.3.4 and Section 3.3.3 for details of how the distributions were calculated. The carbon budget consistent with staying below 1.5 °C warming is based on RCP 4.5 and RCP 8.5 scenarios.

Cumulative emissions from 1870 in PgC
Probability of not exceeding 1.5 ºC

	66%	50%	33%
IPCC SYR	613	613	695
ALL models	606	627	680
OC models	610	638	684

Cumulative emissions from 2011 in PgC
Probability of not exceeding 1.5 ºC

	66%	50%	33%
IPCC SYR*	98	98	179
ALL models	209.5	277.3	329.3
OC models	200.1	277.3	332.5

Cumulative emissions from 2015 in PgC **
Probability of not exceeding 1.5 ºC

	66%	50%	33%
IPCC SYR*	55	55	136
ALL models	170	237	289
OC models	160	237	293

Table 3. The observationally-constrained models (OC models) are based on 2006-2015 test, as shown in Figure 3 of the main text, and (ALL models) refer to the RCP 8.5 and RCP 4.5 multi-model, multi-ensemble results reported in this study.

Note: An amount of 555 PgC has been emitted for the period 1870-2015 (IPCC AR5, 2013; Le Quéré et al., 2015). The amounts reported from IPCC SYR, 2013 are subject to +/- 5 PgC uncertainty due to conversion between $GtCO_2$ and PgC, since the $GtCO_2$ amounts were originally reported to the nearest 10 $GtCO_2$, in IPCC SYR.
*The IPCC SYR results are from Table 2.2 from the IPCC Fifth Assessment Synthesis Report (2014), based on responses from ESMs and EMICs to RCP 8.5 scenario, originally reported in GtCO2, rounded to the closest 50 $GtCO_2$.
**Cumulative emissions from 2011 in the IPCC SYR row were calculated by subtracting 1890 GtCO2 that was emitted for the period (1870-2011), from the IPCC SYR values since 1870, as in Rogelj et al., 2016.
**Cumulative emissions from 2015 in the IPCC SYR row were calculated by subtracting 2050 $GtCO_2$ that was emitted for the period (1870-2015), from the IPCC SYR values since 1870, as in Rogelj et al., 2016. Note: The numbers presented here are subject to rounding

Sensitivity to the period chosen

To avoid a bias due to the base period chosen in the consistency test (Sections 4.3.2 and 4.3.3) used to calculate the present level of warming, we performed additional analysis for two other base periods: 1995-2006, and 2002-2011, during which the observed warming was compared with the model responses. The correlation between the specific level of warming for a given period (Figure 33; horizontal axis), and the 1.5° C carbon budgets exists irrespective of the chosen period, but it gets stronger as we move closer towards the recent decade (Figure 33; panel a). The models that warm the most for a given level of carbon emitted in any of the three periods considered (left hand side of the figures), are also furthest away from the respective observational estimates of cumulative fossil fuel emissions (dashed lines). The cumulative frequency distribution of carbon budgets (similar to the one presented earlier in Figure 31), based on the consistency test carried out for each of the three different base periods is shown in Figure 33. As noted before, changing the anomaly base period to the recent decade (Figure 33, bottom four bars) has a significantly larger impact on the remaining carbon budgets (that indicate a greater amount of carbon remaining, compared to the carbon budgets relative to 1861-1880 anomaly period). Historical observationally-constrained tests (for 1995-2006 and 2002-2011 periods) show very similar range of carbon budgets as the ones based on the consistency test rests for the recent decade (2006-2015) with only a small re-distribution of model weights, due to a slightly different subset of models used. Therefore, the choice of the base period for which the temperatures are compared between the model responses and observations does not significantly affect the model results.

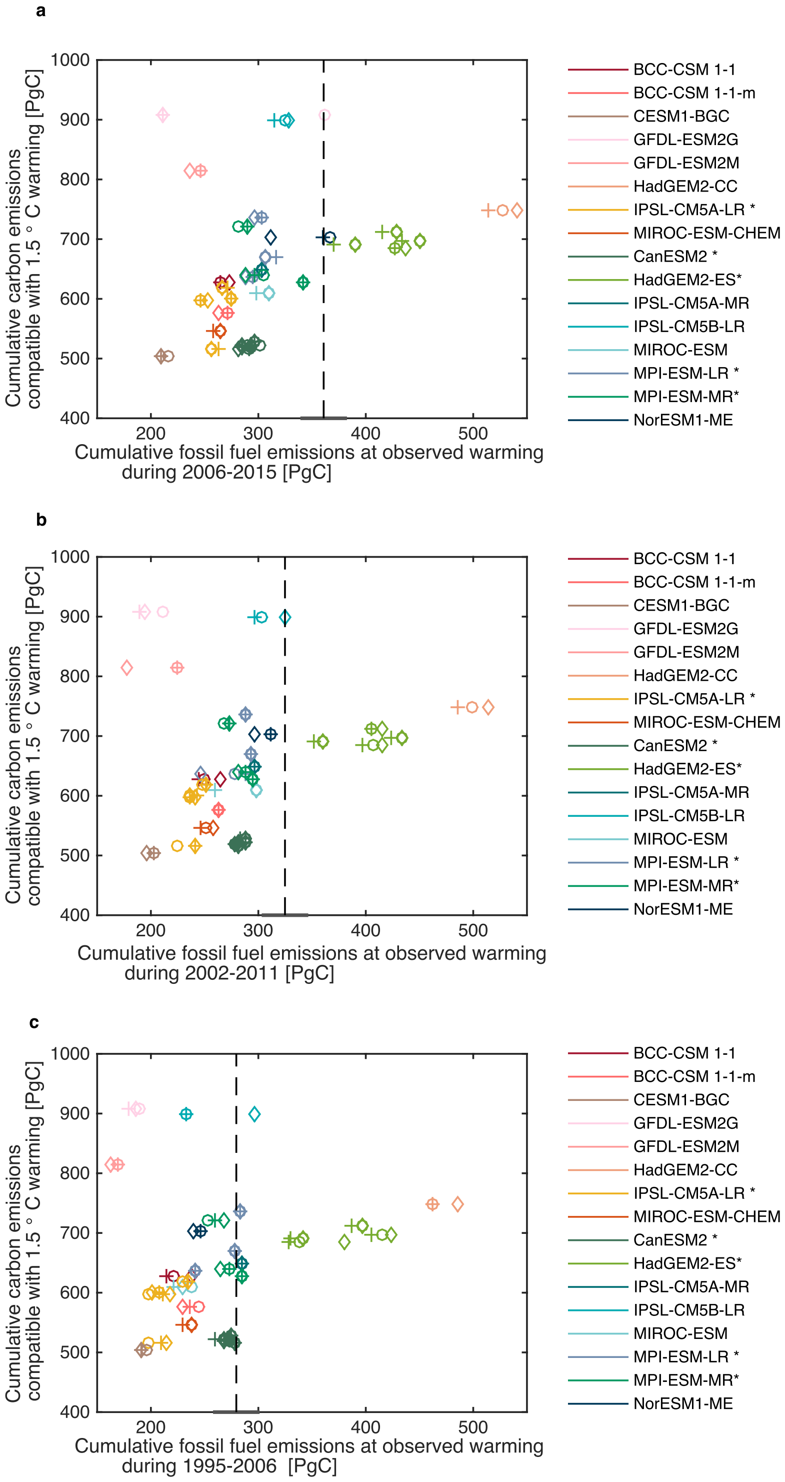


Figure 32. Simulated cumulative fossil-fuel carbon emissions at present warming (horizontal axis), and cumulative total carbon budgets consistent with 1.5 °C warming (vertical axis) for RCP 4.5 scenario, which had the largest amount of models and ensemble members available.

Figure 32 Panel a: the dashed line indicates an estimate of the observed historical cumulative fossil fuel emissions for the period 1870-2010 with the median value of 360.8 PgC (Ref. 10), where year 2010 represents the middle of the recent decade (the ± 20 PgC uncertainty of this estimate is indicated by the horizontal black bar).
Panel b: similarly to panel a, dashed line indicates an estimate of cumulative fossil fuel emissions for the period 1870-2006, where year 2006 represents the middle of the 2002-2011 period.
Panel c: similarly to panel a, dashed line indicates an estimate of cumulative fossil fuel emissions for the period 1870-2000, where year 2000 represents the middle of the 1995-2006 period.
Different symbols (indicated in the legend) represent cumulative emissions budgets calculated using different observational data sets of temperature. Models shown in shades of blue or green passed the consistently test based on 2006-2015 period (see Section 4.3.4), while models in shades of red and orange failed it.
Note: the colour scheme for panels b and c is identical to that one in panel a, to avoid confusion.

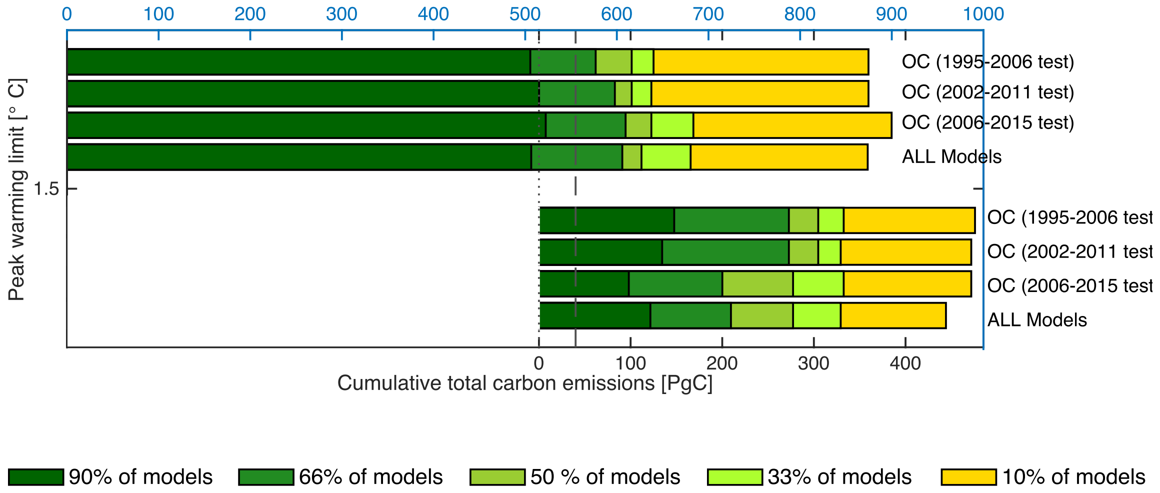


Figure 33. Consistency test: sensitivity to the base period chosen. Cumulative frequency distribution of carbon budgets consistent with staying below 1.5 °C global warming based on all (unconstrained) CMIP5 models considered here (ALL, lower bars for each pair), and observationally-constrained carbon budgets based on models consistent with observations (OC, upper bars for each pair), for two different base periods: 1861-1880 (top four bars), and 2006-2015 (bottom four bars). The grey dashed line indicates the observational total cumulative carbon emissions for the period 1870-2015, with the median value of 555 PgC (Ref. 10), while the dotted line indicates cumulative carbon emissions up to year 2010. The top two bars show carbon budgets relative to 1861-1880 decade (blue axis), in PgC. The bottom two bars show carbon budgets relative to the recent decade 2006-2015, offset by the IPCC estimate of the cumulative carbon emissions up to 2010, which represents the middle of that decade. The lower axis shows carbon budgets relative to year 2015, while the top axis shows budgets relative to 1861-1880. See Section 3.3.3 for details of how the distributions were calculated. The carbon budget consistent with staying below 1.5 °C warming is based on RCP 4.5 and RCP 8.5 scenarios. Note: The OC bars are based on the observationally-constrained test that was carried relative to three different periods chosen (as indicated in the brackets).

Sensitivity to the significance level

In a similar fashion, the analysis was repeated regarding sensitivity of the results regarding the significance level chosen in the consistency test (Section 4.3.4), which are shown in Figure 34. While the significance level affects the total amount of models that pass the test, with higher p-values favouring more models passing the consistency test, the differences between the carbon budgets calculated for different levels of significance are still smaller than the differences arising due to changing the base period relative to the most recent decade (bottom four bars, Figure 34).

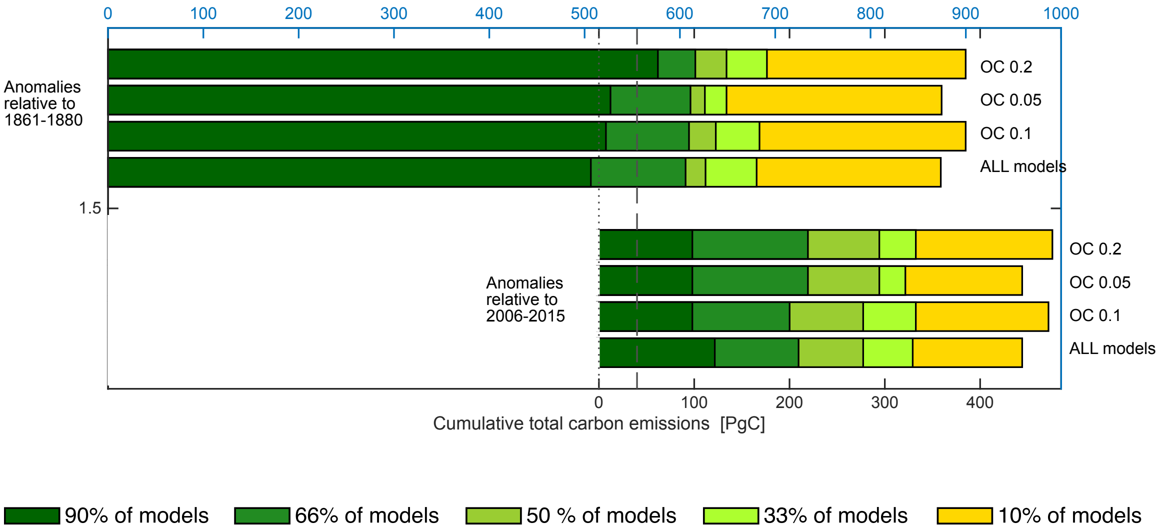


Figure 34. Consistency test: sensitivity to the significance level chosen. Cumulative frequency distribution of carbon budgets consistent with staying below 1.5 °C global warming based on all (unconstrained) CMIP5 models considered here (ALL, lower bars for each pair), and observationally-constrained carbon budgets based on models consistent with observations (OC, upper bars for each pair), for two different base periods: 1861-1880 (top four bars), and 2006-2015 (bottom four bars). The grey dashed line indicates the observational total cumulative carbon emissions for the period 1870-2015, with the median value of 555 PgC (Ref. 10), while the dotted line indicates cumulative carbon emissions up to year 2010. The top two bars show carbon budgets relative to 1861-1880 decade (blue axis), in PgC. The bottom two bars show carbon budgets relative to the recent decade 2006-2015, offset by the IPCC estimate of the cumulative carbon emissions up to 2010, which represents the middle of that decade. The lower axis shows carbon budgets relative to year 2015, while the top axis shows budgets relative to 1861-1880. See Section 3.3.3 for details of how the distributions were calculated. The carbon budget consistent with staying below 1.5 °C warming is based on RCP 4.5 and RCP 8.5 scenarios. Note: The OC bars are based on the observationally-constrained test that was carried relative to three different significance levels (as indicated next to the OC labels).

4.5. Discussion and Conclusions

4.5.1. CMIP5 biases and early 21st century warming

Recent studies indicate factors such as combination of changes in radiative forcing, ocean heat uptake, natural climate variability and incomplete observational coverage (Santer et al., 2014; Medhaug et al, 2017), as potential reasons of why CMIP5 models warm more than observations especially for the period 1998-2012, which defines the so-called ‘warming hiatus’ (Medhaug et al., 2017).

Radiative forcing in RCP scenarios that were used to drive CMIP5 models, beyond year 2005 is not based on observations, and may slightly overestimate the net forcing by not taking into account small volcanic eruptions that have negative radiative forcing (primarily due to sulphate aerosols) (Santer et al, 2014).

Observational temperature series are subject to biases due to incomplete observational coverage, favouring sampling slower-warming regions, and over the ocean, which warms less than land (Huber and Knutti, 2014). However, we made an effort to calculate the present warming from the models based on the same coverage as the observational temperature data, in order to avoid this bias of unequal coverage. Even more robust comparison could be done by avoiding the combination of air and water measurements (blending), and instead, separately calculating the warming over land and sea-surface temperature over the oceans (Huber and Knutti, 2014).

Natural climate variability also plays a role, especially when considering warming on shorter time-scales, as large thermal inertia of the ocean results in decadal-scale internal variability in the ocean temperatures and heat uptake, masking the anthropogenic signal for decades (Medhaug et al, 2017). A short period as an decade is also a subject to decadal processes such as a negative phase of inter-decadal pacific oscillation (IPO), which was present doing the last decade, thereby resulting in recent warming somewhat lower than expected (Meehl et al., 2013). Considering longer time-periods (20-years or more) would make the results more robust to uncertainties arising from natural variability of the climate system.

We address these issues disused above in the consistency test, by considering three different test periods (Section 4.4.3), and our results do not differ substantially among the different testing periods chosen. Although cumulative carbon budgets calculated relative to the base period of recent decade (2006-2015) may be subject to the impact of the internal variability, we sample over internal variability by considering different ensemble members of the models that had such data available, so we would not expect the actual budget to be outside of the PDF presented here. If internal variability caused a cooling over the base period (2006-2015), our mean budget would tend to be biased towards the high end.

4.5.2. Other caveats

Exceedance vs. Avoidance carbon budgets

The carbon budgets reported here can be classified as the threshold exceedance budgets (TEB) (defined in Section 1.4), since they are based on the RCP scenarios, which exceed the 1.5 °C warming level in the subsequent years. Since these scenarios include both CO_2 and non-CO_2 forcing, the carbon budgets presented here are subject to uncertainties in the future non-CO_2 forcing pathways, which are likely to decline as carbon emissions cease (Rogelj et al., 2016). An alternative approach would be calculating threshold avoidance budgets (TAB) (defined in Section 1.4), based on CO_2 and non-CO_2 pathways that never exceed the 1.5 °C level of warming, however, such simulations are not available for the set of comprehensive Earth System Models considered here.

The estimates presented here could be considered somewhat conservative, as non-CO_2 forcing is likely to decline with declining CO_2 emissions, before the allowable amount of carbon is emitted. Since non-CO_2 forcings vary over time, TABs and TEBs would entail different levels of non-CO_2 forcings at the time when the given temperature target is reached. The level of non-CO_2 forcing on average would be higher in TEB approach (Rogelj et al., 2016). However, when considering a sufficiently large sample of different scenarios, there are no substantial differences between TAB and TEB carbon budgets (Rogelj et al., 2016).

Permafrost carbon cycle feedbacks

CMIP5 models considered here do not include permafrost carbon feedbacks, that could lead to additional warming (MacDougall et al., 2012), estimated to range from 0.13 to 0.27 °C by year 2100, primarily based on RCP 8.5 scenario (Schuur et al, 2015), and hence reduce carbon budgets (MacDougall et al., 2015). However, these feedbacks become more important at higher levels of warming (IPCC AR5, 2013: Collins et al., 2013; Schaphoff et al., 2013), and we would not expect them to have a significant impact on the results for the 1.5 °C carbon budgets. These results are also subject to uncertain future non-CO_2 emissions, which have a net warming effect in RCP scenarios. Even if the future aerosol emissions are significantly reduced, contributing to additional warming, they may result in small reductions of the 1.5 °C carbon budgets reported here, however, we would not expect that effect to be significant, since the radiative forcing from aerosols is only a small fraction of total forcing in RCP scenarios.

4.5.3. General conclusions

To summarise, restricting the analysis to the subset of models whose emissions at the observed level of warming are consistent with observations further increases the remaining median 1.5 °C budget of 55 PgC since 2015, based on the IPCC approach (Table 3), to 83 PgC, if calculated relative to the 1880-1861 anomaly base period. However, changing the anomaly base period to the recent decade (2006-2015), as introduced by Millar et al., 2017, eliminates the uncertainties in the historical temperature and cumulative carbon emissions, and leads to further extension of the median 1.5 °C budget to 240 PgC remaining since 2015. The corresponding budget to likely (>66% probability) remain below 1.5 °C warming is 160-170 PgC. These budgets correspond to 23 and 16 years of emissions at the 2015 level of 10.6 PgC/yr (Le Quéré et al., 2016). These results are subject to internal variability over the past decade, and imperfect representation of radiative forcing from volcanoes, as well as small differences between blended temperatures over land and ocean (discussed in Section 4.5.1). If internal variability caused a cooling over the base period of the recent decade considered here, this would tend to bias the mean carbon budget towards higher values. However, similar magnitudes of remaining carbon budgets were reported by a recent study of Millar et al., 2017, who use an estimate of anthropogenic warming, which is less contaminated by internal variability.

Despite the increase in the median unconstrained IPCC remaining carbon budget we find, we recognize that keeping the global mean temperature increase below 1.5 °C, in accord with the recent Paris Agreement (UNFCC, 2015), would require prompt and substantial reductions in greenhouse gas emissions on a global scale (Rogelj et al., 2015; Sanderson et al., 2016; Schleussner et al., 2016), with global emissions peaking in the next two decades (Rogelj et al., 2015), followed by artificial carbon dioxide removal (i.e. negative emissions) in the latter part of the 21st century (Sanderson et al., 2016; Rogelj et al., 2015b). Nonetheless, by demonstrating that the 1.5 °C carbon budget has not yet been exceeded in observationally-constrained model simulations, and by finding a substantially higher remaining budget than that shown by the IPCC AR5, this study indicates that limiting global mean warming to the 1.5 °C level, and hence limiting associated climate impacts (Schleussner et al., 2015), is more feasible than previously thought.

Chapter 5. General Conclusions

5.1. Summary and Significance of Key Findings

The cumulative emissions framework identifies carbon budgets, or a total amount of carbon that can be emitted, compatible with stabilization of the global mean temperature at a desired level. This framework is highly policy-relevant, and it has been widely used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) to specify global carbon budgets consistent with not exceeding different levels of warming.

The work presented in this dissertation addressed three key aspects of the cumulative emissions framework (or TCRE framework). The key conclusions, their significance, and contributions to advancement of knowledge resulting from each project are summarized in the three following sections:

> Section 5.1.1: Summary and significance of key findings in Project I: Assessing linearity of TCRE at high amounts of cumulative carbon emissions (based on Chapter 2).
>
> Section 5.1.2: Summary and significance of key findings in Project II: Understanding the influence of non-CO_2 forcings on cumulative emission budgets reported by the IPCC (based on Chapter 3).
>
> Section 5.1.3: Summary and significance of key findings in Project III: Observationally constraining cumulative carbon budgets consistent with the 1.5 °C warming (based on Chapter 4).

The final Section 5.2 contains a synthesis of results from these three projects, and provides directions for future research.

5.1.1. Project I: Summary and significance of key findings

The approximately linear relationship between warming and total amount of carbon emitted has previously only been demonstrated for cumulative emissions of up to about two trillion tonnes of carbon, and previous studies suggested that the ratio of warming to cumulative emissions may decline at higher levels of total amount of carbon emitted, due to logarithmic dependence of radiative forcing on CO_2, and the effect of saturation of radiative forcing, dominating over the effect of saturation of natural carbon sinks (Herrington and Zickfeld, 2014).

Project I (Assessing linearity of TCRE at high amounts of cumulative carbon emissions; Chapter 2) addressed the robustness of the TCRE framework at high levels of cumulative carbon emissions, and compared the responses of comprehensive Earth System Models, with the Earth system models of intermediate complexity, when analyzing climate system responses at such high levels or carbon emitted. Our results showed that the relationship between warming and the total amount of carbon emitted continues to be approximately linear even up to five trillion tonnes of carbon emitted, based on the responses from comprehensive Earth System Models and some Earth System Models of intermediate complexity. These findings imply that the TCRE framework widely used in the IPCC Fifth Assessment Report is robust even at high levels of carbon emitted, and provides a useful tool for policymakers, allowing them to specify carbon budgets consistent with not exceeding a given level of peak warming on a global scale.

To date, action to mitigate climate change has been limited, and in deciding on climate policy, it is important to ask the question, what would be the consequences if no action to mitigate climate change were taken? Project I addressed this question and demonstrated that if no further climate mitigation actions are pursued on a global scale, and the Earth's remaining fossil fuel resources continue to be combusted under a business-as-usual scenario, the resulting changes in the climate system are very profound, with the global mean warming due to CO_2 alone ranging from 6.4 °C to 9.5 °C, the Arctic warming between 14.7 °C to 19.5 °C, and substantial precipitation changes, in response to 5 EgC emitted, where 5 EgC represents the lower bound of the fossil fuel resource estimate. These changes would likely be large enough to render many areas of the globe uninhabitable, and to have extremely profound impacts on ecosystems and agriculture (Sherwood et al., 2010).

5.1.2. Project II: Summary and significance of key findings

The Summary for Policymakers from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC SPM, 2013) primarily reports CO_2-only carbon budgets consistent with different levels of peak warming, which were based on TCRE estimates from model responses and observations. Non-CO_2 forcings have a net warming effect (in RCP scenarios), thereby, leading to reductions in carbon budgets consistent with not exceeding different levels of peak warming. Carbon budgets that account for forcing from both CO_2 and non-CO_2 agents, reported in IPCC SMP, were derived directly from RCP simulations, which is not consistent with the CO_2-only carbon budget estimates described above.

Project II (Understanding the influence of non-CO_2 forcings on cumulative emission budgets reported by the IPCC; Chapter 3) addresses this gap in consistent calculations and understanding differences between CO_2-only carbon budgets, and carbon budgets based on simulations that include both CO_2 and non-CO_2 forcing. This project also quantified the effects of non-CO_2 greenhouse gases on carbon budgets compatible with not exceeding 1.5 °C and 2.0 °C warming due to CO_2 alone, and in simulations that also include non-CO_2 forcings, using simulations from comprehensive Earth System Models, firstly, based on the responses from the Canadian Earth System Model (CanESM2) driven by Representative Concentration Pathways (RCP) scenarios, and secondly, based on responses from comprehensive Earth System Models (CMIP5).

While the reductions in carbon budgets due to the net warming effect of the non-CO_2 forcing are sensitive to non-CO_2 forcing trajectories, future mitigation efforts in both CO_2 and non-CO_2 greenhouse gases will play a crucial role in determining how much carbon can be emitted on a global scale not to exceed a given warming threshold.

5.1.3. Project III: Summary and significance of key findings

Cumulative emissions budgets consistent with remaining below 1.5 °C global warming, according to the Paris Agreement, are of considerable interest both within the climate science community and among policymakers (Rogelj et al., 2016; Schleussner et al., 2016). However, carbon budgets reported in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5, 2013), are directly based on simulations from comprehensive Earth System Models (CMIP5), which, in general, tend to warm more than observations for the current amount of carbon emitted (IPCC, 2013), thereby tending to underestimate carbon budgets consistent with staying below a given level of peak warming. The IPCC Fifth Assessment Report showed a median cumulative emissions budget to remain below 1.5 °C global warming of approximately 69 PgC remaining after 2015 (IPCC, 2013: Summary for Policymakers, TFE.8, Figure 1), or approximately 6.5 years of emissions at the 2015 level from 2015 onwards, and indicated that the 10th percentile of the 1.5 °C emissions budget had already been exceeded by the end of 2011. Based on this it might be inferred that limiting global warming to below 1.5 °C is almost impossible.

The goal of Project III (Observationally constraining cumulative carbon budgets consistent with the 1.5 °C warming; Chapter 4) was to observationally- constrain model output and calculate carbon budgets based on responses of the comprehensive Earth System Models (CMIP5) that are consistent with observations of cumulative fossil fuel emissions for the present level of warming, to provide more robust estimates of the carbon budgets consistent with not exceeding the 1.5 °C warming threshold. Eight of the 16 models considered here passed the consistency test that determined which models are consistent with observations based on their amount of cumulative fossil fuel emissions at the present level of warming. The 1.5 °C carbon emission budgets based on the CMIP5 models which are consistent with observations, and relative to the most recent decade (following Millar et al., 2017), show a higher median remaining amount of carbon that can be emitted than that inferred from the IPCC AR5 (Collins et al., 2013).

The results of this project showed that observationally-constraining model responses and changing the base period to the recent decade increases the median carbon budgets consistent with 1.5 °C peak warming level to 249 PgC, compared to the median carbon budgets shown in the IPCC report of approximately 69 PgC (IPCC, 2013) remaining after 2015. Thus, while limiting median projected global warming to below 1.5 °C is undoubtedly challenging (Rogelj et al., 2016), our results indicate it is not impossible as might have been inferred from the IPCC carbon budget estimates.

5.2. Synthesis of Results and Future Directions

5.2.1. Synthesis of Results

The work presented in this dissertation addressed three key aspects of the cumulative emissions framework, focusing on its robustness at high amounts of carbon emitted (well above the 2000 PgC limit; Project I), the role of non-CO_2 forcings (Project II), and the role of observational constrains on the TCRE framework, and carbon budgets that are derived from it (Project III).

In general, these three studies confirm the robustness and wide applicability of the TCRE framework, and its policy-relevant implications for carbon budgets consisting with limiting the global mean warming to a given level.

While the uncertainties related to permafrost carbon cycle feedbacks, that are not represented by the models considered here, or uncertainties arising from sensitivity of the results to future non-CO_2 emission trajectories still need to be taken into account, the carbon budget framework provides very useful information for addressing the question of global importance: how much carbon can be emitted in total, before certain warming thresholds (such as the 1.5 °C warming target, as specified by the Paris Agreement) are reached. Therefore, the results presented in this dissertation are of high societal relevance, and provide new lines of evidence for robustness of the carbon budgets (TCRE) framework under different conditions described above.

5.2.2. Future directions

Further work with the upcoming the sixth phase of the Coupled Model Intercomparison Project (CMIP6) experiments (Eyring et al., 2016) will provide even more opportunities for future analysis of TCRE and the resulting carbon budgets, and their observational constraints under this framework. In particular, future research including analysis of the carbon budgets under the newly designed Shared Socioeconomic Pathways (SSP scenarios; O'Neill et al., 2016) will provide insights into effects of non-CO_2 forcings under different future emission scenarios, which largely vary in the level of non-CO_2 forcings as well as future aerosol trajectories (Riahi et al., 2016). The comprehensive Earth System Models in the CMIP6 project are expected to include a more complex representation of the climate system, and possibly include models with permafrost feedbacks, which would provide even more robust results for this type of analysis.

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