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Tokarska Katarzyna B. (Orcid ID: 0000-0001-8887-8798)
Rogelj Joeri (Orcid ID: 0000-0003-2056-9061)

Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot

Katarzyna B. Tokarska[1,2,3], Kirsten Zickfeld[2] and Joeri Rogelj[4,5]

[1] Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

[2] Department of Geography, Simon Fraser University, Burnaby, B.C., Canada

[3] School of Geosciences, University of Edinburgh, Edinburgh, UK

[4] Grantham Institute, Imperial College London, London SW7 2AZ, UK

[5] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria

Corresponding author: Katarzyna B. Tokarska (kasia.tokarska@env.ethz.ch)

Key Points:

- The global mean temperature is, in principle, reversible after an overshoot, but carbon sinks show path-dependence
- Carbon budgets in overshoot scenarios are independent of CO_2-emission pathway for low levels of overshoot (up to 300 PgC)
- No corrections are needed for ambitious mitigation scenarios with low levels of overshoot presented in the IPCC Special Report on 1.5 °C

Abstract

Emission pathways that are consistent with meeting the Paris Agreement goal of holding global mean temperature rise well below 2 °C often assume a temperature overshoot. In such overshoot scenarios, a given temperature limit is first exceeded and later returned to, under the assumption of large-scale deliberate Carbon Dioxide Removal from the atmosphere (CDR). Here we show that although such strategy might result in a reversal of global mean temperature, the carbon cycle exhibits path-dependence. After an overshoot, more carbon is stored in the ocean and less on land compared to a scenario with the same cumulative CO_2 emissions but no overshoot. The near-path independence of surface air temperature arises despite the path dependence in the carbon cycle, as it is offset by path dependence in the thermal response of the ocean. Such behaviour has important implications for carbon budgets (i.e. the total amount of CO_2 emissions consistent with holding warming to a given level), which do not differ much among scenarios that entail different levels of overshoot. Therefore, the concept of a carbon budget remains robust for scenarios with low levels of overshoot (up to 300 PgC overshoot considered here) but should be used with caution for higher levels of overshoot, particularly for limiting the environmental change in dimensions other than global mean temperature rise.

Plain Language Summary

Many of the CO_2 emission pathways that are consistent with the 1.5 °C and 2 °C temperature limit in the long term are based on an assumption that emitting CO_2 and removing it later from the atmosphere leads to the same state of the climate system. Such removal of excess carbon dioxide (CO_2) from the atmosphere is possible, in principle, by the implementation of technologies that deliberately remove CO_2 from the atmosphere (referred to as CDR), resulting in net-negative emissions. Here we study climate response to overshoot scenarios, where a given temperature level is temporarily exceeded and then restored by CDR. We show that carbon cycle responses depend on the CO_2 emission pathway, and the magnitude of the overshoot. However, the global mean temperature response is reversible and independent of CO_2 emission pathway. This has important implications for carbon budgets (i.e. the total amount of CO_2 emissions that can be emitted to limit global mean warming to a given level). We show that carbon budgets do not differ much among scenarios whereby a given target is reached after temporary overshoot, and non-overshoot scenarios.

1 Introduction

Following the Paris Agreement's long-term temperature goal of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and 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; Rogelj et al., 2018), numerous studies published possible emission pathways for limiting warming to below 2 °C or to 1.5 °C. The Paris Agreement's long-term temperature goal does not suggest that a given level of temperature rise may be temporarily exceeded, but studies have made various assumptions leading to pathways that either stay below or temporarily exceed the 1.5°C or 2°C limits (Grubler et al., 2018; Luderer et al., 2018; Rogelj et al., 2018; Sanderson et al., 2016; Sanderson et al., 2017). The precise interpretation of the Paris Agreement's long-term temperature goal remains a topic of active discussion in policy circles (Schleussner et al., 2016; Rogelj et al., 2017).

Meeting the Paris Agreement's long-term temperature goal requires ambitious mitigation efforts on a global scale (Rogelj et al., 2016). Reducing emissions drastically over the coming decades requires more investment in the near term compared to a situation in which action is postponed and emission reductions are assumed to be implemented later. Because of the way mitigation pathways were designed, there are structural biases towards delaying emission reductions (Rogelj et al., 2019). These biases could be resolved if scenarios would apply a different and more appropriate scenario logic (Rogelj et al., 2019). However, emission pathways often first breach the intended temperature target level with the assumption that temperatures can be returned to the desired temperature target level by the year 2100 (Rogelj et al., 2018; Sanderson et al., 2016, 2017; Tanaka & O'Neill, 2018). Such pathways are referred to as overshoot pathways because they temporarily exceed the target temperature level and aim at stabilizing temperature rise at a level lower than the target later on. Geophysically, an overshoot can only be achieved through the implementation of deliberate Carbon Dioxide Removal from the atmosphere (CDR) (Matthews & Solomon, 2013), which results in net-negative emissions for a given period. (For a comprehensive summary of various CDR technologies and their feasibility see Minx et al., 2018; Fuss et al., 2018). If overshoot is avoided, the reliance on CDR is reduced (Grubler et al., 2018; Strefler et al., 2018; Vuuren et al., 2018).

While temperature rise has been shown to be reversible in scenarios that implement CDR, other components of the climate system, such as sea level rise (Tokarska & Zickfeld, 2015;

Ehlert & Zickfeld, 2018; Mengel et al., 2018; Palter et al., 2018) or ocean acidification (Mathesius et al., 2015) and marine net primary productivity (John et al., 2015) take centuries to millennia to be restored to their initial levels, even under large-scale implementation of CDR. Recent studies examined the carbon-climate responses to CDR (Vichi et al., 2013; Tokarska & Zickfeld, 2015; Jones et al., 2016; Zickfeld et al., 2016; Schwinger & Tjiputra, 2018), indicating that carbon sinks often weaken, as expected, when atmospheric CO_2 is deliberately reduced, or even become sources of carbon (i.e. release CO_2 back to the atmosphere) in response to deliberate net removal of the anthropogenic CO_2 from the atmosphere (Tokarska & Zickfeld, 2015; Jones et al., 2016).

The reversibility of climate change in response to CDR has implications for the concept of a carbon budget (i.e. the total amount of CO_2 that can be emitted, consistent with achieving a given temperature level; Zickfeld, et al. 2009), which has shown to be independent of the CO_2 emission pathway, particularly in scenarios with monotonically increasing CO_2 emission rate. However, the question remains whether the concept of a carbon budget is robust in case of overshoot scenarios. This is particularly pertinent because the carbon budgets concept is applied to emissions pathways that stay below a given target level but also to pathways that temporarily overshoot a specific temperature limit (Rogelj, et al., 2016; Rogelj et al., 2018). An overshoot of a given carbon budget followed by the implementation of CDR resulting in net-negative emissions leads to a temperature overshoot, where a given level of warming is first exceeded and then returned to. Previous work by MacDougall et al., 2015 suggests that carbon budgets after an overshoot are smaller than carbon budgets before the overshoot for scenarios with large levels of overshoot.

Here we use an Earth System Model of intermediate complexity (UVic ESCM, *Methods 2.2*), driven by a set of idealized emission scenarios that exceed a target carbon budget by different amounts and are followed by large-scale global CDR, such that the total amount of CO_2 emitted is the same in each scenario by the year 2200 (or year 2250 in the 1.5°C scenario group, *Methods 2.1*). We explore the response of land and ocean carbon sinks to overshoot scenarios in which different temperature targets of 1.5 °C, 2.0 °C and 2.5 °C are first exceeded and then restored in the long-term. Our main analysis focuses on the 2.0 °C scenario group, and the two remaining groups are shown in the supplementary material. We compare the carbon cycle response in the stylized overshoot scenarios to that in a reference scenario that limits warming to the given temperature target (such as 2.0 °C) without overshoot at the time the same amount of cumulative CO_2 emissions is reached and explore to what extent the difference is dependent on the level of overshoot.

2 Methods

2.1 CO_2 Emission pathways design

We designed three groups of idealized emission scenarios, where fossil fuel CO_2 emissions peak within the next few decades (in years 2018-2030) and decline to zero by the year 2100 through emission reductions and deliberate removal of CO_2 from the atmosphere (CDR), followed by net-negative emissions in the period 2100-2200, and net-zero emissions in the period 2200-3000. Each scenario group was designed to reach the same level of cumulative CO_2 emissions by the year 2200 (or 2250 for the 1.5 °C scenario group), in order to achieve the same long-term temperature stabilization in each scenario, at the desired level (of 1.5 °C, 2.0 °C or 2.5 °C). Each set of simulations includes a reference non-overshoot pathway (‘OS 0’), where the given temperature stabilization level is not exceeded, and emissions are rapidly reduced to net-zero, without resorting to CDR (Figure 1a; Supplementary Figure S1a). These scenarios are designed to explore the carbon cycle consequences of overshoot and are not intended as interpretations of the Paris Agreement.

We define the *overshoot cumulative emissions* as the difference in cumulative CO_2 emissions between the peak cumulative emissions (maximum cumulative CO_2 emissions before net zero for each scenario) and the cumulative emissions in the reference non-overshoot scenario ‘OS 0’ in year 2200, when cumulative CO_2 emissions reach the same level (Figure 1c), or year 2250 for the 1.5 °C scenario group (Supplementary Figure S1c). Scenario names in the legend indicate the amount of *overshoot cumulative emissions*. We focus the main analysis on the 2.0 °C scenario group, and additional figures for the 1.5 °C and 2.5 °C scenarios are shown in the supplementary material. While the scenarios slightly differ in the design, they are comparable for the purpose of this study.

In all scenarios, land-use change (LUC) emissions follow RCP 2.6 (Vuuren et al., 2011) to the year 2100. After the year 2100, LUC emissions are extended linearly to reach zero in the year 2150. Biophysical effects of land use changes are not considered. In addition to CO_2 emissions from fossil fuels and LUC, all scenarios include forcing from sulphate aerosols and non-CO_2 greenhouse gases, with slight differences in aerosol forcing among scenario groups (Supplementary Figure S3). Both forcings are stabilized after the historical period, and set to a constant, year-2010 value, for future years. Natural forcing due to volcanic eruptions is set to zero for future scenarios, as future eruptions are unpredictable. Hence, while our scenario design is well-suited to explore the relative impact of differing cumulative CO_2 emissions, its aim is not to provide carbon budget estimates for specific warming levels, as non-CO_2 warming plays an important role here as well (Rogelj et al., 2015; Rogelj, et al., 2016; Tokarska et al., 2018).

2.2 The University of Victoria Earth System Model

The University of Victoria Earth System Climate Model (UVic ESCM 2.8) is an intermediate complexity model with a horizontal grid resolution of 1.8˚(meridional) x 3.6˚(zonal) (Weaver et al., 2001). The physical model consists of an atmosphere model coupled to an ocean general circulation model (including both organic and inorganic carbon cycle), a sea ice model, and a land surface model together with dynamic terrestrial vegetation (Weaver et al., 2001) and is coupled to models of the marine and terrestrial carbon cycle.

The atmosphere is represented by an energy-moisture balance model with winds prescribed from observation-based data (Weaver et al., 2001). The atmospheric model is coupled to a three-dimensional ocean general circulation model, consisting of 19 vertical levels and global resolution of 1.8˚(meridional) x 3.6˚(zonal) (Weaver et al., 2001). The ocean model is based on the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model 2.2, including both organic (Ocean Ecosystem Biogeochemical Model (OEBM), represented by nutrient, phytoplankton, zooplankton and particle detritus (NPZD) (Schmittner et al., 2008) and inorganic (Orr, et al., 1999) carbon cycle components. The ocean general circulation model is coupled to a sea-ice model (Weaver et al., 2001), which includes thermodynamic components (open water sea ice and its changing area) and dynamic components governed by momentum balance, which respond to oceanic and atmospheric (wind) stresses (Weaver et al., 2001).

The land surface model, represented by a simplified version of the Hadley Centre Met Office Surface Exchange Scheme (MOSES), is coupled to a dynamic terrestrial vegetation model (Top-down Representation of Interactive Foliage and Flora Including Dynamic vegetation model; TRIFFID) (Weaver et al., 2001; Meissner, et al.,2003; Eby et al., 2009). Changes in temperature and atmospheric CO_2 concentration drive dynamic changes in vegetation distribution, consisting of five different plant functional types (PFTs): broadleaf tree, needle-leaf tree, C3 grass, C4 grass and shrubs (Weaver et al., 2001). The vegetation fraction for each functional plant type is calculated based on Lotka-Volterra competition equations (Meissner et al., 2003). Terrestrial carbon feedbacks due to increased CO_2 levels (CO_2 fertilization) and weakening of the carbon sinks driven by the increase in the temperature are also included (Matthews & Caldeira, 2008). Ice sheets, land-based ice dynamics and carbon release from peatlands and permafrost are not included in this version of the UVic model.

Compared with other Earth System Models of Intermediate Complexity (EMICs), the UVic model ranks high with regards to the complexity of the ocean, land surface and biosphere components, and generates responses that fall within the uncertainty envelope of the observed surface air temperature in the historical period (Eby et al., 2013). In more comprehensive Earth System Models (ESM), the representation of carbon cycle feedbacks spans a range of responses especially regarding uncertain terrestrial carbon uptake. The UVic model carbon cycle responses are generally close to the median of the ESM range (Arora et al., 2013).

3 Results

3.1. Global mean responses to overshoot scenarios

By design, CO_2 emission pathways (Figure 1a) differ in the peak emissions rate and the amount of CDR implemented in the period 2100-2200, resulting in net-negative emissions during that period, in order to reach the same level of cumulative CO_2 emissions (Figure 1c) by the year 2200 (or year 2250 in the 1.5°C scenario group, Supplementary Figure S1, *Methods*). As a result, the 2 °C temperature level is temporarily exceeded in all but the 'OS 0' scenario (Figure 1d), which we will refer to as the reference non-overshoot scenario and to which the overshoot scenarios will be compared. All scenarios reach the same temperature level in the long-term, around the year 2200 (Figure 1d) because each of them emits the same amount of cumulative CO_2 emissions (Figure 1c). Gobal mean warming has been shown to be proportional to the cumulative CO_2 emissions (with the proportionality constant referred to as the Transient Climate Response to cumulative CO_2 Emissions or TCRE (Matthews et al., 2009), and is independent of CO_2 emission pathway for a range of emissions scenarios (Zickfeld, et al., 2012; Herrington & Zickfeld, 2014), particularly for monotonically increasing CO_2 emission rates. Overshoot scenarios considered here exhibit the same proportionality of global mean warming to cumulative CO_2 emissions, despite their non-monotonic nature of CO_2 emission rate, which peaks and declines. Such behaviour of overshoot scenarios has important implications in the context of carbon budgets, which we discuss in section 3.5.

3.2 Carbon reservoirs response

Land carbon storage declines in all overshoot scenarios during the net-negative emissions phase (2100-2200), while the ocean continues to take up carbon for most scenarios albeit at a lower rate than before CDR was implemented (Figure 2). Scenarios with the highest level of overshoot (OS 300, and OS 150) experience a slow-down (or even a sink-to-source transition) in ocean carbon uptake during the CDR phase, which however is followed by an increase in the rate of ocean carbon uptake beyond the year 2200, once the net-negative emission phase stops. After CO_2 emissions return to zero in 2200, land carbon storage continues to decline, whereas ocean carbon storage slowly increases for centuries onwards (Figure 2 b,c). After year 2200 (when CDR ends, and all scenarios reach the same level of cumulative CO_2 emissions) land carbon storage in all overshoot scenarios is lower than in the reference non-overshoot scenario ‘OS 0’, while ocean carbon storage is higher in all overshoot scenarios than in the ‘OS 0’ reference scenario (Figure 2 b,c).

Such behaviour occurs due to the interactions between the atmosphere, ocean and land carbon pools. Atmospheric carbon in the year 2200 is lower in the overshoot scenarios than in the reference non-overshoot scenario (‘OS 0’; Figure 2 a) due to the slow response of ocean CO_2 uptake to CDR. Lower atmospheric CO_2, in turn, leads to a greater loss of land carbon in overshoot scenarios, compared with the reference scenario, as vegetation productivity decreases due to a diminished CO_2 fertilization effect when atmospheric CO_2 levels decline (Jones et al., 2016). However, ocean carbon uptake continues in the long-term (after the CDR phase), and is higher in overshoot scenarios than in the reference non-overshoot scenario, due to its long response timescale. The overall carbon cycle response is qualitatively similar in the 1.5 °C and 2.5 °C scenario groups (Supplementary Figures S1 and S2). We acknowledge that the net amount of these changes is small (Figure 2), and internal variability is not represented in the UVic model. However, ongoing work with large initial conditions ensembles of comprehensive Earth System Models suggests that the effects of internal variability on cumulative land and carbon uptake are small and likely insignificant.

3.3 Restoration of carbon reservoirs to reference levels

To further investigate and quantify the differences in carbon reservoirs in response to overshoot scenarios, we calculated the change in carbon storage relative to the non-overshoot reference scenario ‘OS 0’ in the year 2200 when CDR ends and cumulative CO_2 emissions reach the same level for all scenarios in the 2.0 °C scenario group (Figure 2 d). The difference between the given scenario and the reference scenario increases with increasing overshoot level, with the scenario ‘OS 300’ having the largest difference (~20 PgC) relative to the non-overshoot reference case ‘OS 0’, despite cumulative CO_2 emissions being the same in all scenarios in the year 2200 (Figure 2 d). Similar results are found for the 1.5 °C and 2.5 °C scenario groups. Time-series of this imbalance (i.e. normalized changes of the carbon storage time-series relative to the non-overshoot ‘OS 0’ scenario) are shown in Supplementary Figure S4.

Differences between each overshoot scenario and the non-overshoot reference scenario ‘OS 0’ in the year when CDR ends and cumulative CO_2 emissions reach the same level in all scenarios (i.e. in the year 2200 for the 2 °C and 2.5 °C scenario groups, and in the year 2250 for the 1.5 °C scenario group; Figure 1 and Supplementary Figure 1) are plotted as a function the cumulative CO_2 emissions overshoot in Supplementary Figure S8. There is an approximately linear relationship between the amount of overshoot and the departure from the non-overshoot level for atmosphere, land and ocean carbon storage, which holds across scenario groups. For temperature (Figure S8 b) the linear relationship holds only within each scenario group, due to slightly different scenario design (*Methods*, Supplementary Figure S3).

3.4 Spatial responses to overshoot scenarios

The lag in the ocean thermal response is evident in Figure 3 (left; panels a,c,e), where scenarios with high level of overshoot (e.g. ‘OS 300’, Figure 3 e) store more heat in the upper 1000-2000 m, particularly between 50°S and 50°N and at northern high latitudes, relative to the non-overshoot reference scenario in the year 2200 when CDR ends and cumulative carbon emissions in all scenarios reach the same level. Conversely, the low overshoot scenarios (e.g. ‘OS 150’, Figure 3 a) show a negligible lag in thermal response and return to the non-overshoot temperature level almost immediately after the same level of cumulative emissions is reached. Ocean carbon storage in overshoot scenarios is lower at the surface of the tropical and mid-latitude oceans and larger at the subsurface and in the Arctic relative to the reference scenario (Figure 3; panels b,d,f). The magnitude of those changes becomes more pronounced as the overshoot level increases. Lower carbon storage at the surface is consistent with the lower atmospheric CO_2 concentration in the year 2200 in overshoot scenarios. Heat and carbon storage at the subsurface in the tropical ocean may be associated with the slow mixing of heat and carbon into the surface, possibly amplified by higher stratification, which prevents heat and carbon from returning to the atmosphere (Mathesius et al., 2015) . stratification. The lag in the ocean carbon uptake persists on long timescales, with the high overshoot scenarios returning to the non-overshoot reference level beyond the year 3000 (i.e. 800 years after the end of CDR) (Supplementary Figure S7).

Regionally differences in land carbon uptake relative to the reference non-overshoot ‘OS 0’ scenario can be substantial (up to 20% in the ‘OS 300’ scenario; Figure 4 right panels). However, since the changes are of different signs (negative in the Tropics, positive at high latitudes), the globally averaged change is small. Terrestrial carbon storage in the Tropics is lower in the high overshoot ‘OS 300’ scenario than in the reference non-overshoot scenario ‘OS 0’ due to lower net primary productivity in those regions in scenarios that entail high amounts of CDR (such as in the ‘OS 300’ scenario). These changes are likely driven by a diminished CO_2 fertilization effect: as the atmospheric CO_2 concentration drops below the level in the reference scenario, the net primary productivity of tropical forests declines. In contrast, northern high latitude regions show slightly enhanced terrestrial carbon uptake (north Europe and North America), likely due to warmer conditions at the time of overshoot, which could promote increased productivity for boreal forest (Arora & Boer, 2014) that continues to grow after emissions start to decline as a lagged response to earlier favorable conditions.

3.5 Implications for carbon budgets in overshoot scenarios

The near path independence of surface air temperature (Figure 1d) arises despite the path dependence in the carbon cycle, as it is offset by path dependence in the thermal response of the ocean (i.e. lower levels of atmospheric CO_2 in high overshoot scenarios are compensated by a lagged ocean thermal response; Figure 3). This has important implications for carbon budgets, which have not been analyzed in depth under overshoot scenarios.

Carbon budgets before and after an overshoot can be calculated using the relationship between warming and total cumulative CO_2 emissions (TCRE) (Figure 5a), and are illustrated in Figure 5b for the 2.0 °C warming target, and in Supplementary Figures S5 and S6 for the two remaining scenario groups (for reaching the 1.5 °C and 2.5 °C warming levels). The pre-overshoot carbon budgets were calculated in the year prior to exceeding the given warming target (i.e. 2.0 °C in Figure 5) for the first time, while the post-overshoot carbon budgets were calculated in the year when temperature falls below that target level of warming (i.e. 2.0 °C in Figure 5) for the first time after the overshoot. Our results show that the post-overshoot carbon budgets are largely scenario independent for the low levels of overshoot considered here (up to 300 PgC of overshoot).

This near path-independence of pre- and post-overshoot carbon budgets occurs despite the hysteresis behaviour in TCRE after an overshoot (Figure 5a), with the post-overshoot TCRE curve above the pre-overshoot TCRE (Figure 5a). However, this hysteresis is a result of the scenario design rather than a property of the Earth system. In all scenarios considered here, the non-CO_2 forcing is held at a constant level. The high overshoot scenarios reach the 2 °C target (for the first time, before the overshoot) early on, when the additional warming contribution from non-CO_2 forcing is smaller, and hence, the pre-overshoot carbon budget is greater than their post-overshoot carbon budget. Conversely, low overshoot scenarios reach the 2 °C target (for the first time, before the overshoot) later on, and thus experience a larger contribution of additional warming from non-CO_2 forcing, making the pre- overshoot carbon budget smaller. Also, the additional warming from non-CO_2 forcings is larger in the year 2200 than at the time when the 2 °C target is first reached (before the overshoot). Hence, the post-overshoot carbon budgets can be expected to be smaller than the pre-overshoot budgets, as shown in Figure 5b. The post-overshoot budgets differ little between scenarios (Figure 5b), reflecting the reversibility of global mean temperature at the time the same cumulative emissions are reached, and its pathway independence to CO_2-only scenarios. In the absence of non-CO_2 forcing, the pre- and post- overshoot TCRE curves would likely be co-linear, for the levels of overshoot considered here (up to 300 PgC of overshoot).

These results are in contrast to the results from earlier studies (MacDougall et al., 2015; Zickfeld, et al., 2016), that found considerable differences between the pre- and post-overshoot carbon budgets in scenarios that entail much larger amount of overshoot (e.g. with reductions of the 2.0 °C carbon budget by 785 PgC when estimated from an RCP8.5 CO2-only scenario simulation that included an overshoot of approximately 4000 PgC; MacDougall et al., 2015). These studies, however, consider much larger levels of overshoot, for which surface air temperature is not fully restored at the time the reference CO2 concentration is reached. Furthermore, plausible amounts of CO_2 emission reductions through implementation of CDR after an overshoot are estimated to range from about 10 to 1000 GtCO2 (27-270

PgC; Rogelj et al., 2018) over a time-frame until the year 2100. Our study shows that for low levels of overshoot (up to 300 PgC overshoot considered here), the post-overshoot carbon budgets are nearly independent of the CO_2 emission pathway or the level of overshoot (Figure 5b). Consequently, the concept of a carbon budget remains a robust way for expressing emissions limits consistent with limiting the global mean temperature rise to the desired level in such scenarios. This path independence of overshoot carbon budgets for specific temperature limits when low levels of overshoot are considered arises despite path dependence of carbon cycle responses, which is compensated by the delayed response of the ocean resulting from inertia in the ocean heat uptake, discussed in the previous section.

3.6 Sources of uncertainty

In our experimental design, aerosols and non-CO_2 greenhouse gases follow the historical trajectory and are held constant (at year-2010 value) in the future years (*Methods*). In reality, non-CO2 forcing would likely change along with CO_2 emissions, which would introduce nonlinearities to the TCRE framework, which is applicable predominantly for CO_2-only emissions. The pre-overshoot and post-overshoot budgets are likely to differ among scenarios if time-varying non-CO_2 forcings were considered.

While the primary effect of non-CO_2 forcing is their direct temperature effect (warming or cooling), non-CO_2 agents are also shown to affect the carbon sinks uptake rate through the warming effect (Gillett & Matthews, 2010; MacDougall & Knutti, 2016; Tokarska et al., 2018). Changes in temperature and carbon reservoirs are sensitive to the choice of non-CO_2 emission trajectory, which makes the application of a carbon budget for policy dependent on several aspects other than CO_2 emissions (MacDougall et al., 2015; Mahowald et al., 2017; Mengis et al., 2018; Tokarska et al., 2018). Aerosols also impact the carbon cycle through deposition (Mahowald et al., 2017).

Another source of uncertainty arises from permafrost carbon cycle feedbacks (not included in this version of the model), which are shown to be also dependent on the CO_2 emission pathway (MacDougall et al., 2015; Gasser et al., 2018), and may result in additional loss of soil carbon in the permafrost region, especially under scenarios that do not entail ambitious mitigation (Comyn-Platt et al., 2018; McGuire et al., 2018). Especially in case of large overshoot of carbon budgets and thus a reliance on large amounts of CDR, additional release of permafrost carbon may be higher than in the case of low or non-overshoot scenarios (Gasser et al., 2018).

Our simplified scenario design is based on the assumption that CO_2 is removed from the climate system without considering a specific CDR technology, though, in principle, direct capture of CO_2 from the air would have a similar effect. Costs of implementation of CDR at a large scale and challenges and risks related to CO_2 storage or its utilization once it is captured are not considered here.

4 Discussion and Conclusions

Including the possibility of deliberate carbon dioxide removal in the carbon budgets framework, resulting in net-negative emissions, is often based on an assumption that exceeding the carbon budget by one ton of CO_2 implies that exactly one ton of CO_2 needs to be removed through CDR in order to achieve a given temperature target level. Based on such reasoning, delays in reducing emissions over the next decades could be compensated by CDR implementation in the future to remove the budget overshoot.

Our results show that surface air temperature is reversible after an overshoot on global scales. However, the state of the carbon cycle is sensitive to whether a given temperature level is reached for the first time, or whether it is returned to after previously being exceeded (in case of overshoot). Compared to a reference non-overshoot scenario, more carbon is stored in the ocean (with implications for ocean acidification and ocean pH changes) and less carbon is stored on land when the same amount of cumulative emissions is reached. Thus, although the temperature response is largely path independent, carbon cycle responses do show a path dependency. Finally, if permafrost carbon cycle feedbacks were included, this path-dependence would likely be more profound, due to pathway dependence of carbon budgets on CO_2 emissions from permafrost thaw (Gasser et al., 2018; MacDougall et al., 2015). Regional responses also show path-dependence, with high overshoot scenarios taking a long time to return to the non-overshoot level after the net-negative CDR implementation. The ocean heat and carbon reservoir return to the non-overshoot level only centuries after the overshoot. It is worth noting that if CDR were accomplished partly or largely by enhanced rock weathering, there would be a co-benefit in mitigating ocean acidification impacts

(Taylor et al., 2015), which would result in different ocean changes than discussed in this study.

The near-path independence of surface air temperature arises despite the path dependence in the carbon cycle, as it is offset by path dependence in the thermal response of the ocean. Hence, our results suggest that the concept of carbon budgets (i.e. a total amount carbon that can be emitted to meet a given temperature target) remains a valid metric for global temperature rise when considering overshoot scenarios with low levels of overshoot (up to 300 PgC of overshoot considered here). Therefore, for stringent temperature target levels (such as the 1.5 °C and 2 °C targets) and low-overshoot scenarios, carbon budgets are very similar between scenarios with and without overshoot of a temperature target. However, noticeable and potentially important differences arise in the state of the carbon cycle, especially for higher levels of overshoot, with implications for climate change impacts that are directly related to atmospheric CO_2 (e.g. ocean acidification).

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Data Availability

The UVic ESCM model version 2.8 is available at http://climate.uvic.ca/model/2.8/
Model data used in this study will be made publicly available through the <link> repository at the time of publication.

ORCID IDs

Katarzyna B Tokarska https://orcid.org/0000-0001-8887-8798
Kirsten Zickfeld https://orcid.org/0000-0001-8866-6541
Joeri Rogelj https://orcid.org/0000-0003-2056-9061

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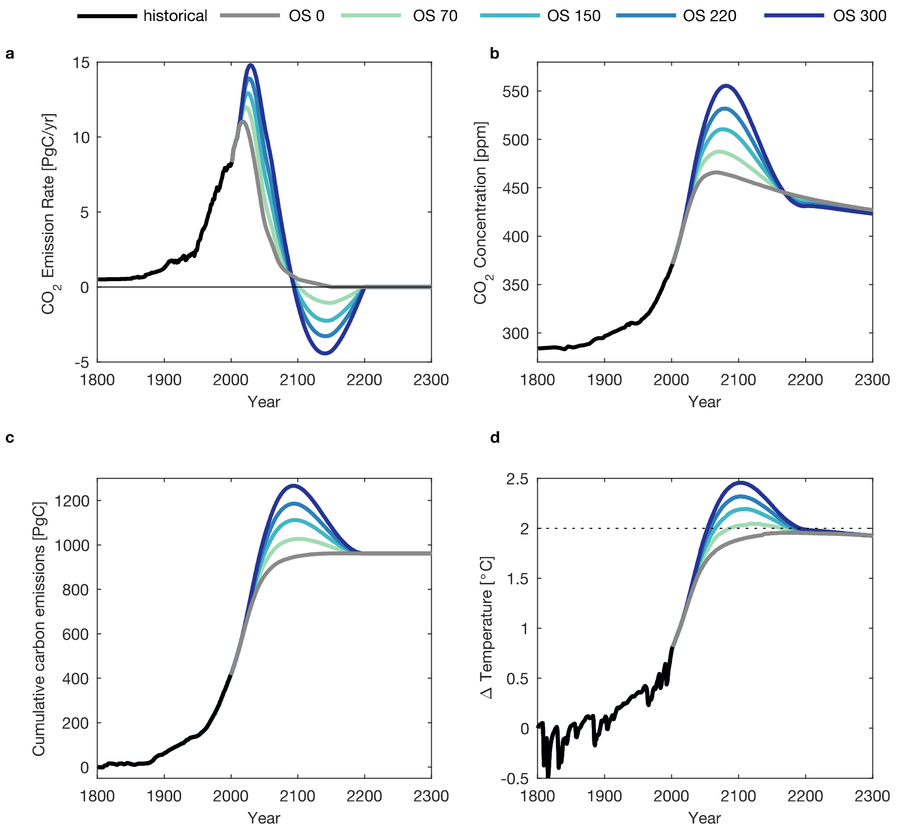

Figure 1. Time series of the global mean (**a**) CO_2 emission rate (fossil fuel and land use change emissions) (**b**) atmospheric CO_2 concentration; (**c**) global mean temperature change relative to 1801; (**d**) cumulative CO_2 emissions since 1801), for the 2 °C scenario group. *Note: Scenario names in the legend indicate the amount of overshoot cumulative emissions (in PgC). Units of PgC are equivalent to GtC.*

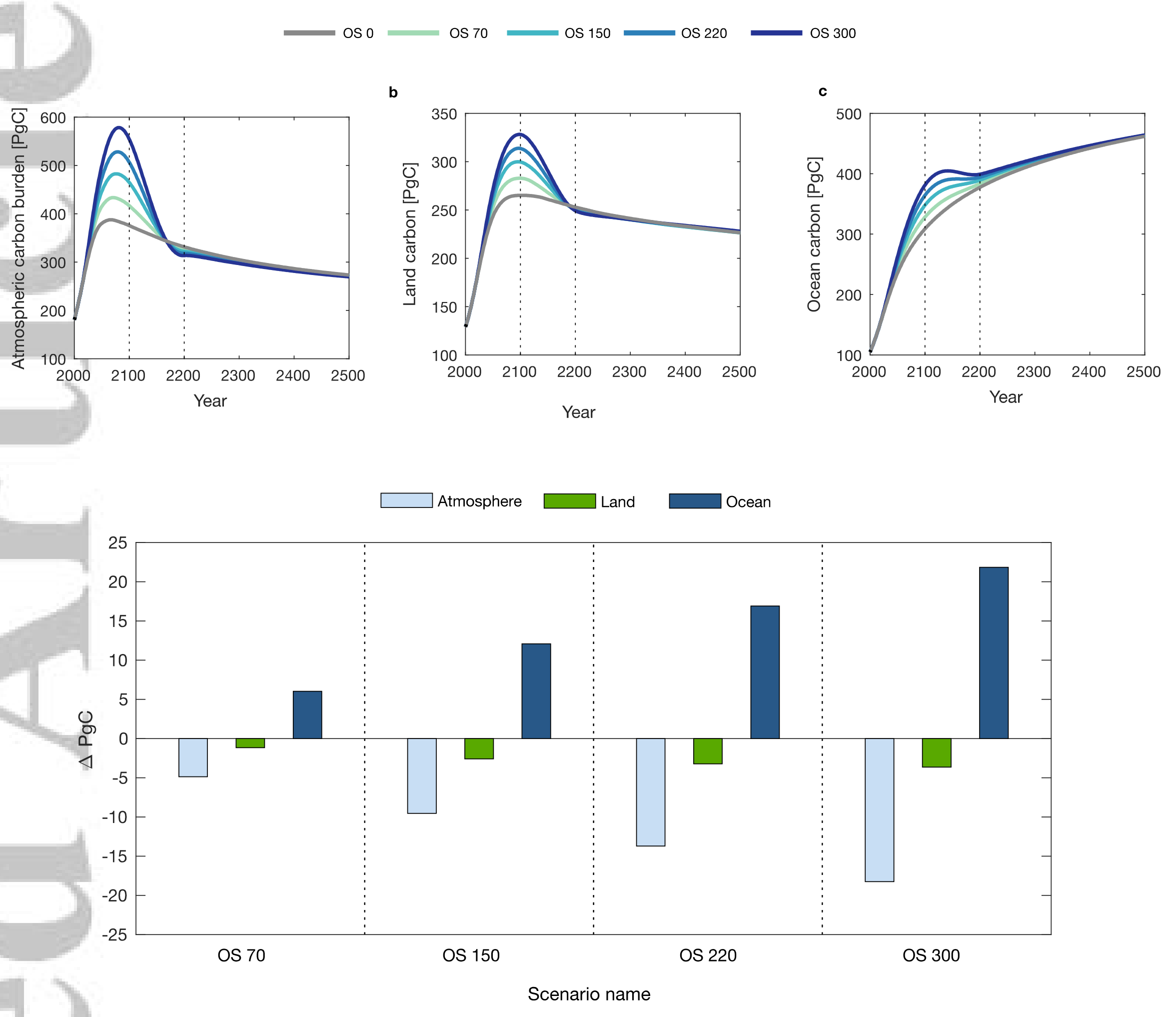

Figure 2 Changes in carbon reservoirs. Atmospheric carbon burden (**a**), Total land carbon storage (**b**), total ocean carbon storage (**c**), as a function of time. Panel (**d**) shows differences in global carbon reservoirs in scenarios with different levels of overshoot (indicated on the horizontal axis) relative to non-overshoot ‘OS 0’ scenario in the year 2200, when the same level of cumulative CO_2 emissions is reached, for the 2 °C scenario group. *Note: Units of PgC are equivalent to GtC. Anomalies in panels (**a-c**) are relative to the year 1801. Dashed lines in panels (**a-c**) indicate times when net-negative CDR is implemented (starting in 2100) and when emissions reach net-zero, and all cumulative emissions are at the same level (in the year 2200), for the 2 °C scenario group.*

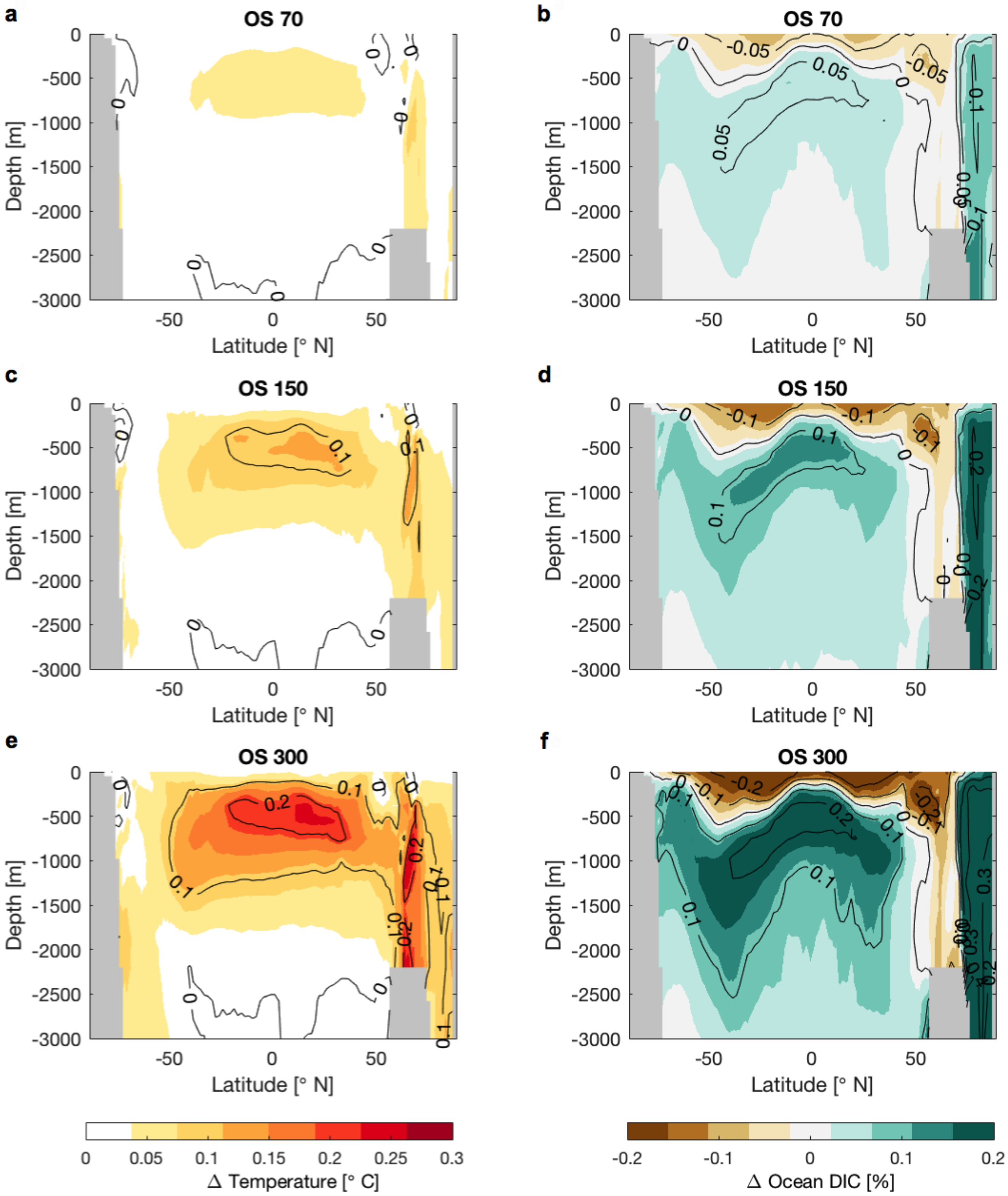

Figure 3. Differences in zonal mean ocean temperature (*left panels* **a,c,e**) and dissolved inorganic carbon (DIC; *right panels* **b,d,f**) in years 2190-2200 (when CDR ends) in scenarios 'OS 70', 'OS 150', and 'OS 300 (as labelled), in the 2 °C scenario group. The differences are shown with respect to the reference non-overshoot scenario 'OS 0'. *Note: CDR ends in the year 2200 when all scenarios reach the same level of cumulative* CO_2 *emissions.*

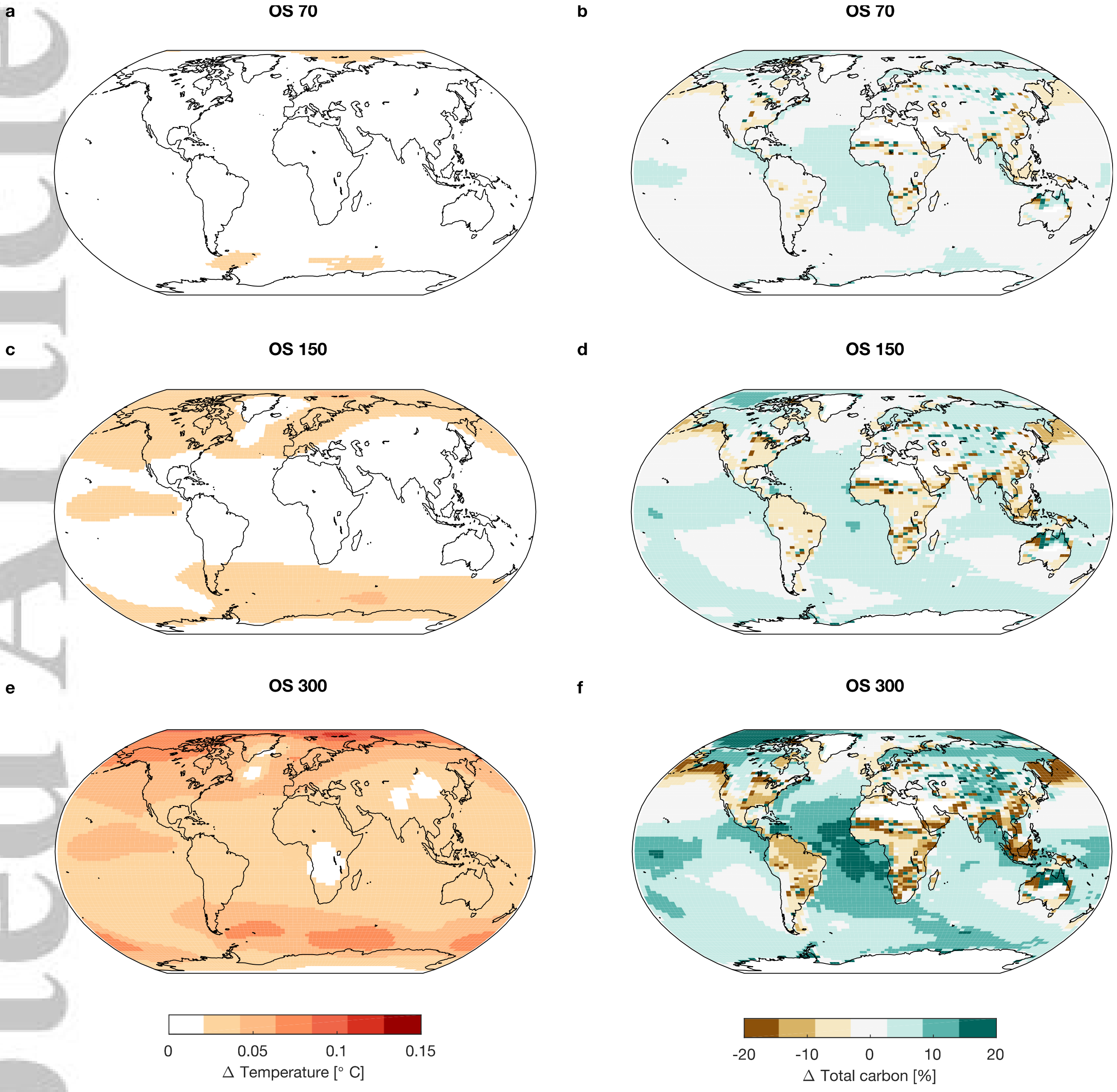

Figure 4. Differences in spatial distribution of surface air temperature (*left panels* **a,c,e**) and total carbon (*right panels* **b,d,f**) relative to the reference non-overshoot scenario 'OS 0' in years 2190-2200, in the 2 °C scenario group, in scenarios 'OS 70', 'OS 150', and 'OS 300; (as labelled). *Note: CDR ends in the year 2200 when all scenarios reach the same level of cumulative* CO_2 *emissions. Total carbon (right panels) is calculated as a sum of soil and vegetation carbon storage on land and vertically-integrated dissolved inorganic carbon (DIC) in the ocean.*

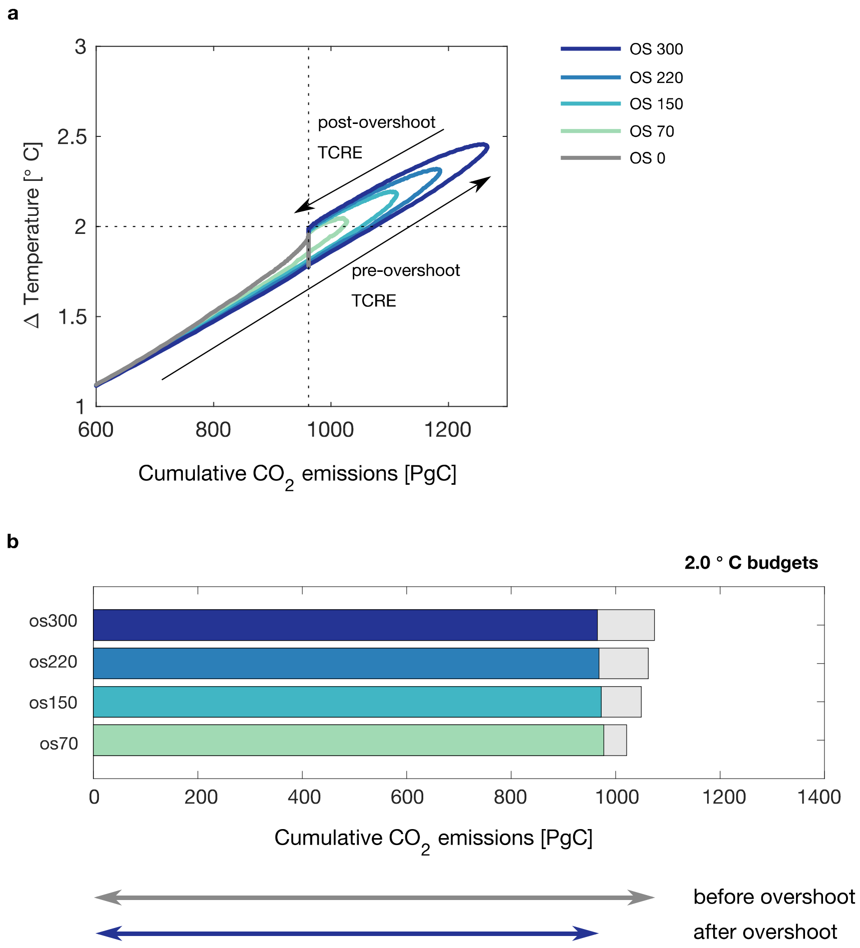

Figure 5. Global mean temperature change as a function of cumulative CO$_2$ emissions (TCRE) (**a**), and the resulting carbon budgets for temperature stabilization at 2.0 °C level (**b**). Grey bars in panel (**b**) indicate carbon budgets calculated before the overshoot, while colored bars indicate carbon budgets after the overshoot for each emission pathway, as labelled. *Note: The grey vertical line in panel (a) is due to a slight decline in temperature once emissions are stopped (As in Figure 1d). Similar behavior occurs for the remaining scenarios once emissions are stopped, and equivalent vertical lines are co-linear with the grey line. See Supplementary Figures S5 and S6 for the other two scenario groups for 1.5 °C and 2.5 °C warming levels*