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## LETTER

# What determines the warming commitment after cessation of $CO_2$ emissions?

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## Abstract

Previous studies have shown that global mean surface air temperature remains elevated after cessation of $CO_2$ emissions. However, studies differ in whether the temperature continues to increase, slowly decreases, or remains constant after cessation of emissions. An understanding of this committed warming is of importance because it has implication for the estimation of carbon budgets compatible with temperature targets. Here, we investigate the effect of the state of thermal and bio-geochemical equilibration at the time emissions are set to zero on the committed warming as the latter is determined by the balance of these two equilibration processes. We find that the effect of thermal equilibration, expressed as fraction of realized warming, dominates over the bio-geochemical equilibration, expressed as ratio of the airborne fraction to the equilibrium airborne fraction. This leads to a positive warming commitment, and a commitment that declines the later emissions are zeroed along a trajectory of constant atmospheric $CO_2$ concentration. We furthermore show that the scenario prior to zeroed emissions has the strongest effect on the warming commitment, compared to the time of zeroed emissions and the time horizon over which the commitment is calculated.

## 1. Introduction

Previous studies have shown that the global mean surface air temperature (GMSAT) remains elevated for several centuries [1–3] after $CO_2$ emissions are set to zero. The GMSAT change remains approximately constant to first order in most studies [4, 5]. However, to second order GMSAT increases or decreases after emissions are zeroed, depending on the model used [6, 7]. This committed change in GMSAT from previous emissions, referred to as zero emission warming commitment (ZEC), is important because it has implications for the carbon budget approach. This approach is based on the finding that the long-term warming is dependent only on the cumulative $CO_2$ emissions and is independent of the emission pathway, implying that there is a fixed amount of cumulative emissions for a certain temperature change target [8, 9]. If there were significant GMSAT increase after emissions cease, this warming commitment would need to be considered and the allowable cumulative emissions would be lower in order to reach the same target.

The ZEC varies largely in sign and magnitude across studies. [2] and [5] showed a ZEC of −0.6°C to 0.1°C for the first-generation Canadian Earth System Model (for the SRES A2 scenario and a range of scenarios with cumulative $CO_2$ emissions of 2500 PgC) whereas [7, 10, 11] find a ZEC of −0.5°C to 0.2°C for the National Centre for Atmospheric Research Climate System Model (for the SRES A2/B1 scenarios and a pulse emission of 1800 PgC) and a ZEC of 0.37°C to 0.5°C for the Earth System Model from the Geophysical Fluid Dynamics Laboratory (ESM GFDL) (for idealized 1% increase scenario to 745 ppm of atmospheric $CO_2$ and pulse emission of 1800 PgC). The range of the ZEC for the different models are due to different scenarios prior to cessation of emissions and setting emissions to zero at different atmospheric $CO_2$ concentrations. [6] showed a warming commitment of −1.2°C to 0.6°C for a number of Earth System Models of Intermediate Complexity (EMICs) using the same scenario. This EMIC range is biased towards negative values as slightly negative instead of zero emissions were prescribed in this study, resulting in a more rapid decrease in atmospheric $CO_2$. These ZEC ranges show that there is no systematic difference in the ZEC depending on whether an EMIC or an ESM is used, as

suggested by [11]. Previous studies indicated that ZEC differences arise from different scenarios prior to cessation of emissions, including different rates and total amounts of emissions [6, 12, 13], the consideration of different forcing agents [6, 14], the magnitude of the forcing [15], and model uncertainties in physical and biogeochemical processes [6, 7].

The time at which emissions are zeroed along a constant $CO_2$ concentration trajectory and the time-span over which the commitment is calculated may also contribute to the differences in the warming commitment but have not been explored previously. The effect of the timing at which emissions cease is not straightforward, as the ZEC is an interplay between physical and bio-geochemical processes. When emissions are zeroed, ocean heat uptake declines which leads to an increase in surface air temperature. This warming effect is counteracted by a decline in atmospheric $CO_2$ concentration due to continuous uptake of carbon by the land and the ocean, which has a cooling effect. Based on the ocean's thermal inertia [16] alone, one would expect the ZEC to decrease the later emissions are zeroed along a constant concentration trajectory because the ocean heat uptake declines less. However, atmospheric $CO_2$ concentrations after emissions are zeroed also decline less the later emissions are zeroed. The ZEC will be determined by the balance of the two processes and it is not immediately clear which one dominates. Previous studies investigate the effect of declining ocean heat uptake but they do not study in detail the change in decline in atmospheric $CO_2$ [11, 17].

The goal of this study is to explore in depth the effect of both thermal and bio-geochemical equilibration and the amount of forcing on the ZEC using the University of Victoria Earth System Climate Model (UVic ESCM). We design two sets of $CO_2$ scenarios that differ in the time emissions are set to zero along a constant $CO_2$ concentration trajectory, and the peak $CO_2$ concentration (and hence radiative forcing). Such a simulation setup allows us to isolate the effect of the state of equilibration on the ZEC.

## 2. Model and Simulations

### 2.1. Model
We carried out all simulations using the University of Victoria Earth System Model, version 2.9 (UVic ESCM 2.9), an Earth system model of intermediate complexity (EMIC). The three main physical components are an atmosphere energy balance model, a general ocean circulation model, and a land surface scheme. The atmosphere is described by a vertically integrated energy-moisture balance model, including water vapour, planetary long wave, and dynamic wind feedbacks. All components have a resolution of 1.8° (meridional) × 3.6° (zonal). The model does not

include an ice sheet model and we only discuss the sea level rise due to thermal expansion of the ocean. UVic ESCM also includes land, ocean, and ocean sediment coupled carbon cycle components, which enable to prescribe $CO_2$ emissions directly instead of $CO_2$ concentrations.

The ocean is described via the Geophysical Fluid Dynamic Laboratory (GFDL) Modular Ocean Model (MOM), a 3D general circulation model with 19 vertical layers [18]. The MOM is coupled to a dynamic sea ice model, a sediment model, an inorganic carbon cycle model, and a marine biology model [19]. The land is modeled via a simplified version of the land surface scheme MOSES (Met Office Surface Exchange Scheme) [20, 21], which is coupled to the dynamic vegetation model TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) [22].
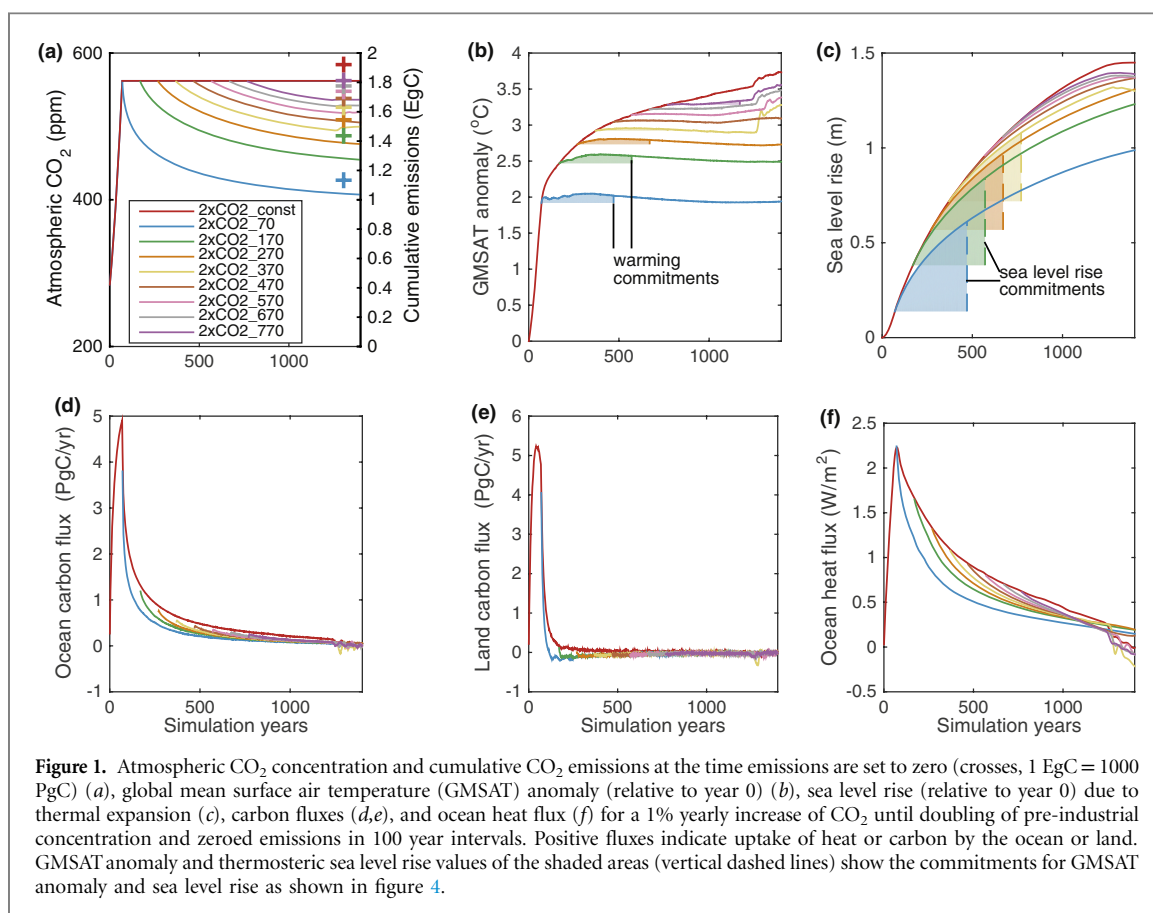
### 2.2. Simulations
The UVic ESCM is spun up for 6000 years under pre-industrial (year 1800) conditions. After the model is fully equilibrated, it is forced with idealized scenarios with a 1% yearly increase in atmospheric $CO_2$ concentration until doubling ($2 \times CO_2$) and quadrupling ($4 \times CO_2$) of the pre-industrial concentration. Starting from these $CO_2$ concentration levels a cessation of $CO_2$ emissions is prescribed in 100 year intervals (figures 1(*a*) and 2(*a*)). The simulations are named according to the simulation year emissions are set to zero, i.e. $2 \times CO_2$_70 until $2 \times CO_2$_770 and $4 \times CO_2$_140 until $4 \times CO_2$_840. Atmospheric $CO_2$ is the only forcing in these simulations. Within each simulation set, either $2 \times CO_2$ or $4 \times CO_2$, simulations differ in the state of thermal and bio-geochemical equilibration of the climate system at the time emissions are set to zero and in the cumulative emissions (figures 1(*a*) and 2(*a*)). Holding atmospheric $CO_2$ constant allows for (small) $CO_2$ emissions that results in different cumulative emissions by the time emissions are set to zero (1138–1926 PgC and 2881–3843 PgC for the $2 \times CO_2$ and $4 \times CO_2$ scenarios, respectively). Other aspects, such as radiative forcing at time of zeroed emissions, are the same. Therefore, this unique simulation set up allows for a detailed examination of the effect of the state of equilibration on the ZEC.

## 3. Results

### 3.1. Climate system response
In our scenarios, an increase in atmospheric $CO_2$ is prescribed, followed by setting $CO_2$ emissions to zero along a constant $CO_2$ concentration trajectory. As soon as $CO_2$ emissions stop, atmospheric $CO_2$ declines due to carbon uptake by land and ocean (figures 1(*a*) and 2(*a*)). Within each simulation, the rate of this $CO_2$ decline decreases over time. The change in the rate of

**Figure 1.** Atmospheric $CO_2$ concentration and cumulative $CO_2$ emissions at the time emissions are set to zero (crosses, 1 EgC = 1000 PgC) (*a*), global mean surface air temperature (GMSAT) anomaly (relative to year 0) (*b*), sea level rise (relative to year 0) due to thermal expansion (*c*), carbon fluxes (*d,e*), and ocean heat flux (*f*) for a 1% yearly increase of $CO_2$ until doubling of pre-industrial concentration and zeroed emissions in 100 year intervals. Positive fluxes indicate uptake of heat or carbon by the ocean or land. GMSAT anomaly and thermosteric sea level rise values of the shaded areas (vertical dashed lines) show the commitments for GMSAT anomaly and sea level rise as shown in figure 4.
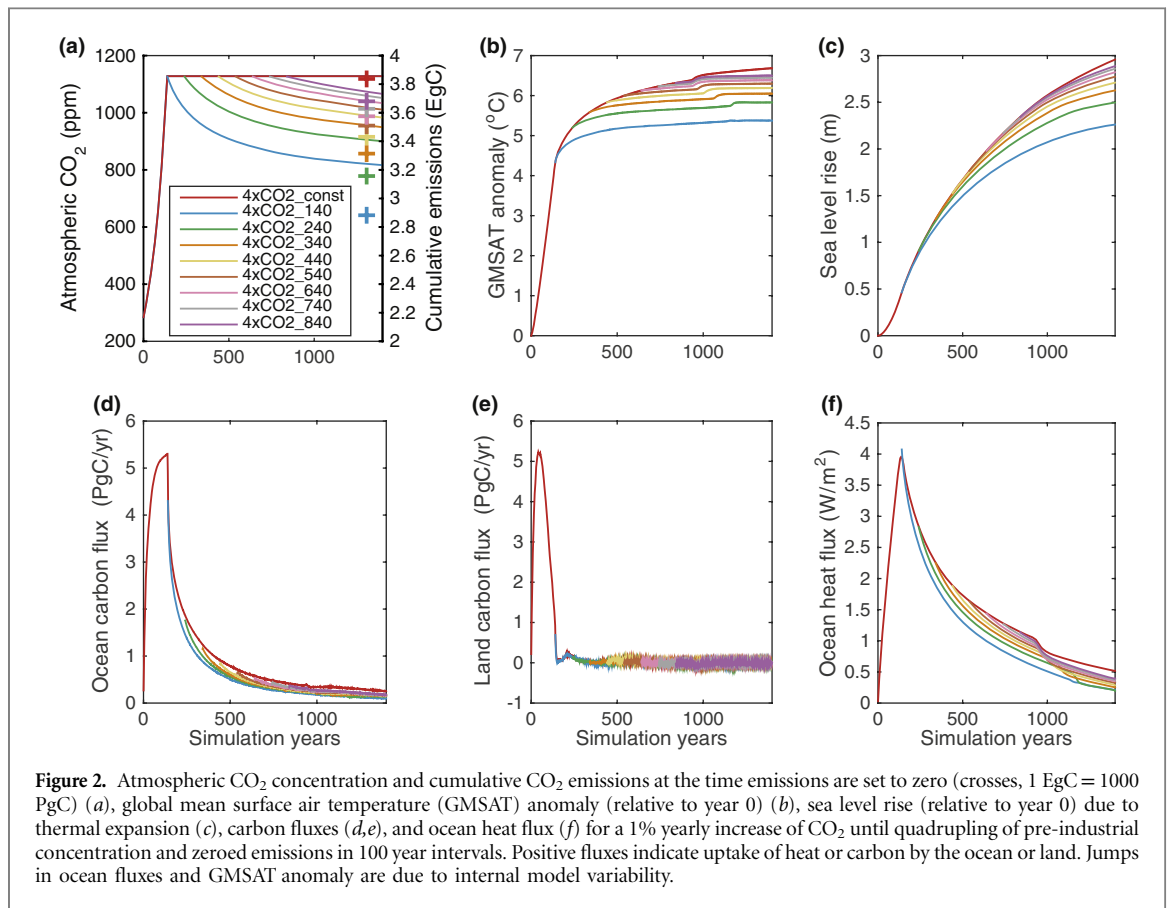
atmospheric $CO_2$ decline is associated with different time scales of carbon uptake processes on land and in the ocean, as discussed below. Additionally, atmospheric $CO_2$ concentration declines less between simulations the later emissions are zeroed.

Despite declining $CO_2$ concentration, GMSAT anomaly continues to rise slightly once emissions cease in all simulations (figures 1(*b*), and 2(*b*)). This warming after zeroed emissions declines between simulations the later emissions are zeroed (figure 4(*a*)). The discontinuities in GMSAT anomaly and other variables towards the end of some simulations are caused by flushing events in the Southern Ocean in the UVic ESCM which depend on the level of atmospheric $CO_2$ [23]. In these events the model abruptly transitions into a stage of strong deep water formation in the Southern Ocean, which leads to outgassing of carbon into the atmosphere, decreased sea ice coverage, and increased air temperature.

Sea level rise due to thermal expansion of the ocean continues after emissions cease in all simulations (figures 1(*c*) and 2(*c*)). The increase rate in thermosteric sea level rise diminishes the later emissions are zeroed. Therefore sea level rise after cessation of emissions is smaller the later emissions are zeroed (figure 4(*b*)).

In order to understand which aspects determine the warming commitment it is important to understand how ocean heat uptake and ocean and land carbon uptake evolve as ocean heat uptake affects GMSAT directly and land and ocean carbon uptakes

affect atmospheric $CO_2$ and in turn radiative forcing and GMSAT. Ocean heat and carbon fluxes decline while atmospheric $CO_2$ is held constant and decline more strongly over time after cessation of emissions within each simulation (figures 1(*d,f*) and 2(*d,f*)). Land and ocean carbon uptake together affect the airborne fraction (defined as ratio of change in atmospheric carbon burden to cumulative $CO_2$ emissions) and atmospheric $CO_2$ concentration after cessation of emissions and thus radiative forcing. The land carbon uptake already starts declining shortly before reaching doubling of pre-industrial $CO_2$ concentration due to positive climate-carbon cycle feedbacks, such as decreased net primary productivity in lower latitudes or increased soil respiration under rising temperatures [24, 25]. Therefore, in the first zeroed emissions simulation of the $2 \times CO_2$ simulations ($2 \times CO_2\_70$) the land carbon flux is still relatively high. Together with high ocean carbon uptake, this high land carbon uptake results in a strong decline in airborne fraction after cessation of emissions (figure 3(*b*)) and low warming commitment for this simulation (figure 5(*a*)). For all other simulations, land carbon flux is very close to zero once emissions cease. The differences in the decline between ocean heat and carbon flux, together with the close to zero land carbon uptake after zeroed emissions have implications on how ocean heat uptake declines compared to the decline in radiative forcing. The implications for the ZEC are discussed in section 3.3.

**Figure 2.** Atmospheric $CO_2$ concentration and cumulative $CO_2$ emissions at the time emissions are set to zero (crosses, 1 EgC = 1000 PgC) (*a*), global mean surface air temperature (GMSAT) anomaly (relative to year 0) (*b*), sea level rise (relative to year 0) due to thermal expansion (*c*), carbon fluxes (*d,e*), and ocean heat flux (*f*) for a 1% yearly increase of $CO_2$ until quadrupling of pre-industrial concentration and zeroed emissions in 100 year intervals. Positive fluxes indicate uptake of heat or carbon by the ocean or land. Jumps in ocean fluxes and GMSAT anomaly are due to internal model variability.

## 3.2. Thermal and bio-geochemical equilibration

In the following we explore how close the system is to thermal and bio-geochemical equilibration at the time $CO_2$ emissions are set to zero and to what extent the state of equilibration determines the sign and magnitude of the warming commitment.
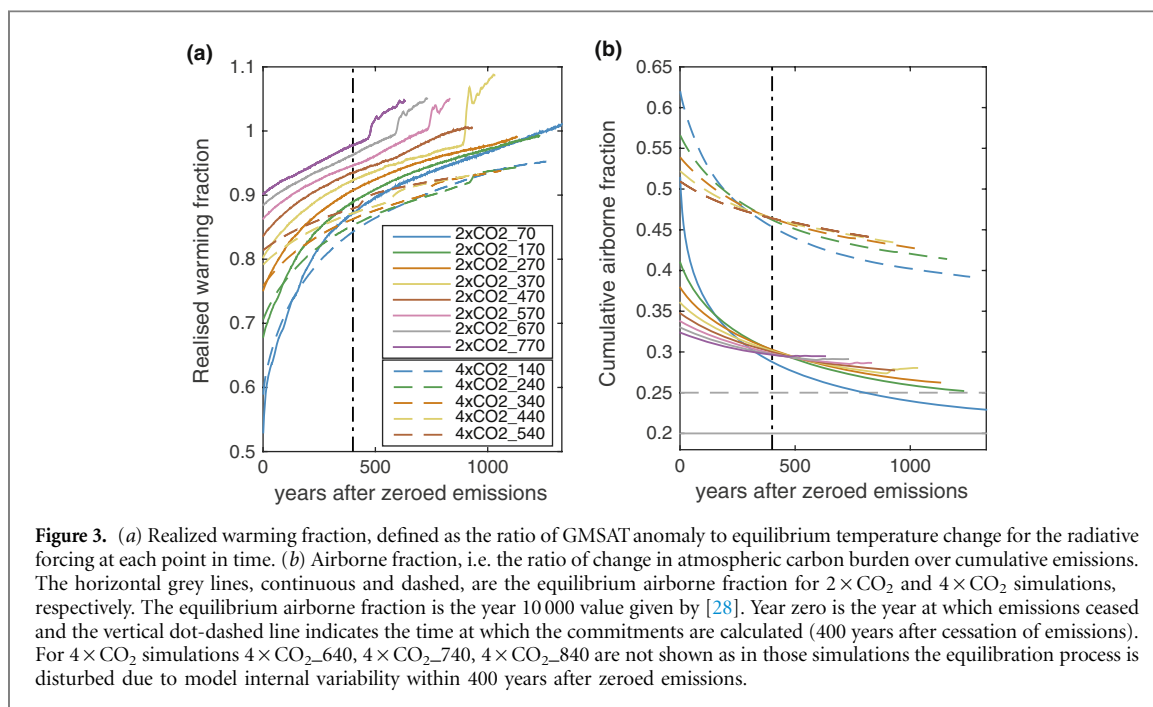
The state of thermal equilibration is expressed in terms of the realized warming fraction, defined as the ratio of GMSAT anomaly to instantaneous equilibrium temperature, which is a commonly used measure [3]. The higher the realized warming fraction, the closer the system is to thermal equilibrium. The equilibrium temperature is calculated using $T_{eq}(t) = RF(t)/\lambda$ where $T_{eq}$ is the equilibrium temperature at time $t$, $RF$ is the radiative forcing at time $t$, and $\lambda$ is the climate feedback parameter. For both $2 \times CO_2$ and $4 \times CO_2$ simulations, the simulations in which emissions cease later are closer to thermal equilibrium at the time of zeroed emissions (figure 3(*a*)). The realized warming fraction at the time of zeroed emissions is 0.5–0.9 and 0.6–0.8 for $2 \times CO_2$ and $4 \times CO_2$ simulations, respectively. Thus the $4 \times CO_2$ simulations have a smaller range but are generally further away from thermal equilibrium than the $2 \times CO_2$ simulations (compare continuous and dashed lines in figure 3(*a*)).

The deviation of the cumulative airborne fraction (*AF*) from the equilibrium cumulative airborne fraction ($AF_{eq}$) is used as a measure for the state of bio-geochemical equilibration (figure 3(*b*)). The *AF* indicates the fraction of cumulative anthropogenic emissions that remains in the atmosphere and is determined by the carbon uptake mechanisms, which act on varying time scales. The main processes that are important on the time scales discussed here are land carbon uptake (1–100 year time scale), dissolution of $CO_2$ into the ocean mixed layer and mixing of carbon into deeper ocean layers (10–1000 years time scale), and reaction of dissolved carbon with calcium carbonate in sea sediments (1000–10 000 years) [26, 27]. Carbon uptake by land weathering (acting on 10 000–100 000 year time scales) plays only a minor role on the time scales considered here. In previous studies [3, 11, 28], the *AF* after 10 000 years was taken as $AF_{eq}$, which does not take weathering into account.

We follow this approach here and use the year 10 000 values given by [28] for the UVic ESCM. [28] show that the $AF_{eq}$ (value at year 10 000) is cumulative emission but not emission path dependent. The $AF_{eq}$ for the $2 \times CO_2$ simulations is ∽20%, the $AF_{eq}$ for the $4 \times CO_2$ simulations is ∽25% (grey lines in figure 3(*b*)). These values agree with the theoretically derived value of 20% by [3]. At the time of zeroed emissions, the *AF* is lower for simulations in which emissions cease later in time indicating that the system is closer to bio-geochemical equilibration (figure 3(*b*)). However, the decline rate of the *AF* is higher the earlier emissions cease because atmosphere and ocean carbon reservoirs are less in equilibrium with atmospheric $CO_2$ and therefore land and ocean carbon uptake is higher. Thus, from 400–500 years after cessation of emissions onwards the *AF* is higher the later emissions cease. The $2 \times CO_2$ and $4 \times CO_2$ simulations reach an *AF* at

**Figure 3.** (*a*) Realized warming fraction, defined as the ratio of GMSAT anomaly to equilibrium temperature change for the radiative forcing at each point in time. (*b*) Airborne fraction, i.e. the ratio of change in atmospheric carbon burden over cumulative emissions. The horizontal grey lines, continuous and dashed, are the equilibrium airborne fraction for $2 \times CO_2$ and $4 \times CO_2$ simulations, respectively. The equilibrium airborne fraction is the year 10 000 value given by [28]. Year zero is the year at which emissions ceased and the vertical dot-dashed line indicates the time at which the commitments are calculated (400 years after cessation of emissions). For $4 \times CO_2$ simulations $4 \times CO_2\_640$, $4 \times CO_2\_740$, $4 \times CO_2\_840$ are not shown as in those simulations the equilibration process is disturbed due to model internal variability within 400 years after zeroed emissions.

the year of zeroed emissions of 30%–50% and 50%–60% respectively. Thus both $2 \times CO_2$ and $4 \times CO_2$ simulations are still quite far from biogeo-chemical equilibrium and the simulations within $2 \times CO_2$ and $4 \times CO_2$ sets do not converge to the same value.

Comparing the realized warming fraction and how close the *AF* is to its equilibrium value at time of zeroed emissions, the system seems to be closer to thermal equilibrium than to bio-geochemical equilibrium. However, this difference in equilibration time scale is inherent to the definition of the $AF_{eq}$ as we include long time scale ocean sediment processes of the carbon cycle by choosing the year 10 000 value as the $AF_{eq}$. Thus the thermal equilibration is faster than the bio-geochemical equilibration due to the long time scales of sediment carbon cycle processes.
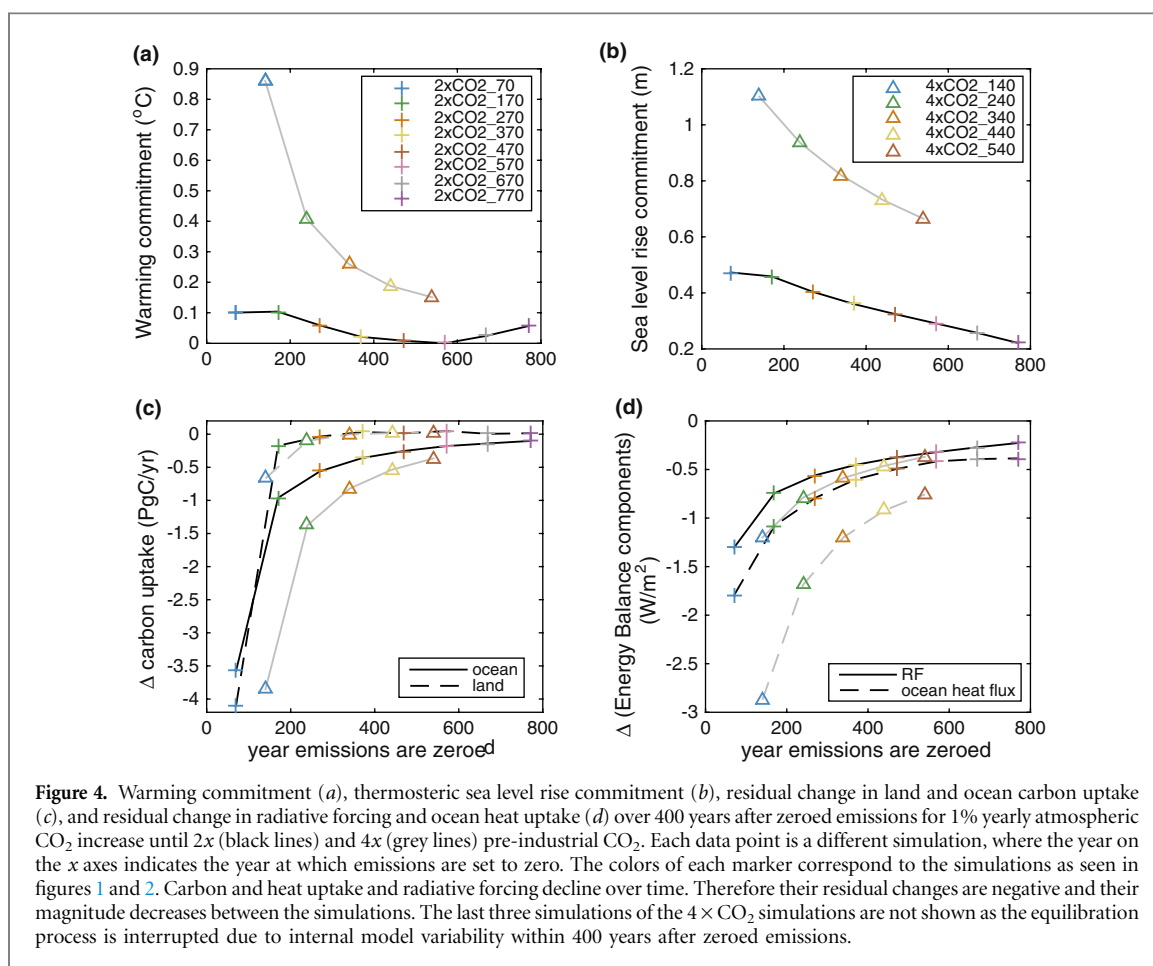
**3.3. Zero emission warming commitment**
In the following we discuss the ZEC and the connection to the equilibration of the climate system. We evaluate the zero emission commitment in this study by calculating the difference of a variable (GMSAT anomaly and sea level rise due to thermal expansion) between the time of setting emissions to zero and 400 years later. If we use commitment in the following, we refer to the zero emission commitment described above and ZEC refers to the zero emission warming commitment as the change in GMSAT anomaly. The ZEC is always positive (figure 4(*a*)) and it is higher for $4 \times CO_2$ simulations than for $2 \times CO_2$ simulations ($4 \times CO_2$ ZEC $= 0.2\,^\circ C - 0.9\,^\circ C$, $2 \times CO_2$ ZEC $= 0\,^\circ C - 0.1\,^\circ C$). Furthermore, the ZEC declines for simulations with emissions zeroed later in time for both $2 \times CO_2$ and $4 \times CO_2$ simulations. Only between the last three $2 \times CO_2$ simulations, the ZEC increases again. Similarly, the thermosteric sea level rise

commitment declines for simulations with emissions zeroed later in time (figure 4(*b*)).

As discussed above, the ZEC results from a balancing process between the decline in ocean heat uptake (warming effect) and the decline in radiative forcing due to declining $CO_2$ concentrations (cooling effect). The decline in ocean heat uptake depends on the state of thermal equilibration of the system, i.e. the more the system is equilibrated, the lower the decline in ocean heat uptake and the smaller is the warming effect from this decline. The degree of decline in atmospheric $CO_2$, on the other hand, is dependent on the state of bio-geochemical equilibration, i.e. the more the system is equilibrated, the smaller is the ocean carbon uptake and thus a smaller decline in atmospheric $CO_2$ and radiative forcing, implying a smaller cooling effect. A positive ZEC, as found in our simulations, indicates that the effect of decline in ocean heat uptake after emissions cease dominates over the effect of decline in radiative forcing within each simulation. Thus the effect of the thermal equilibration dominates over the effect of bio-geochemical equilibration within each simulation.

In the following we show that the dominance of thermal equilibration also explains the decrease in ZEC for simulations where $CO_2$ emissions are set to zero later with a few exceptions in the $2 \times CO_2$ simulations.
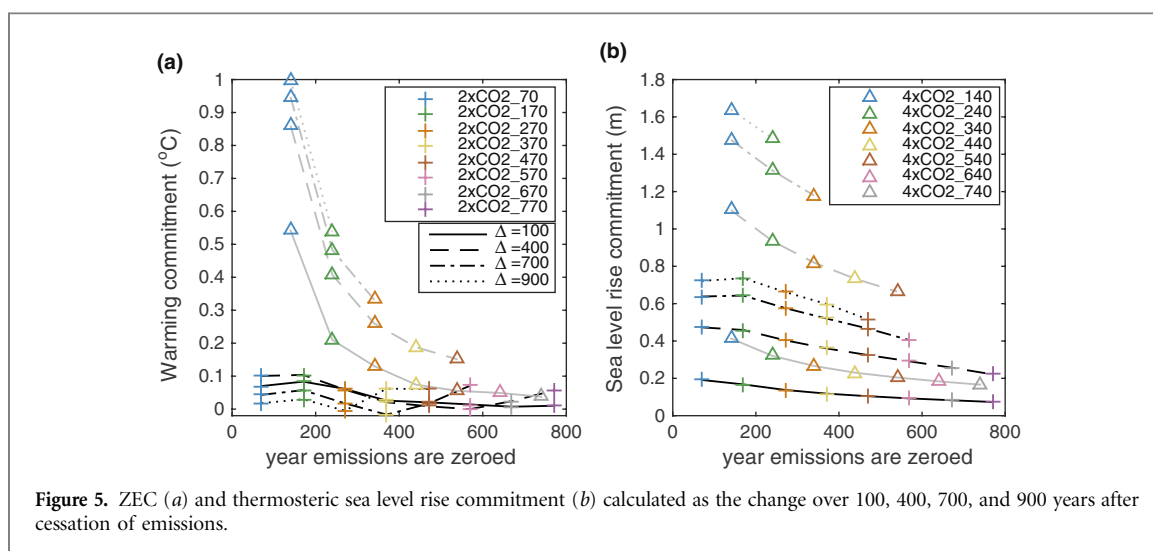
The decline in radiative forcing diminishes the later emissions are zeroed along a constant $CO_2$ trajectory because the decrease in carbon uptake diminishes the later emissions cease (figure 4(*c*)). The decline in ocean heat uptake also diminishes the later emissions are zeroed and it diminishes more strongly between simulations than the decline in radiative forcing (compare slopes of continuous and dashed line

**Figure 4.** Warming commitment (*a*), thermosteric sea level rise commitment (*b*), residual change in land and ocean carbon uptake (*c*), and residual change in radiative forcing and ocean heat uptake (*d*) over 400 years after zeroed emissions for 1% yearly atmospheric $CO_2$ increase until $2x$ (black lines) and $4x$ (grey lines) pre-industrial $CO_2$. Each data point is a different simulation, where the year on the *x* axes indicates the year at which emissions are set to zero. The colors of each marker correspond to the simulations as seen in figures 1 and 2. Carbon and heat uptake and radiative forcing decline over time. Therefore their residual changes are negative and their magnitude decreases between the simulations. The last three simulations of the $4 \times CO_2$ simulations are not shown as the equilibration process is interrupted due to internal model variability within 400 years after zeroed emissions.

in figure 4(*d*)). Therefore, the warming effect of the decline in ocean heat uptake decreases more strongly relative to the cooling effect from declining radiative forcing and the ZEC declines the later emissions are zeroed.

There are two exceptions from this decline in ZEC in the $2 \times CO_2$ simulations. Firstly, the ZEC increases between the last three $2 \times CO_2$ simulations (figure 4(*a*)), which is due to an approximately constant decline in ocean heat uptake between those simulations while the decline in radiative forcing continues to decrease (the continuous black line in figure 4(*d*) still changes while the dashed black line is constant). The second exception is approximately constant ZECs between the first two $2 \times CO_2$ simulations due do similarly strong changes in ocean heat uptake decline and radiative forcing decline between those simulations. The stronger decline in radiative forcing after zeroed emissions in the first $2 \times CO_2$ simulation is probably due to a higher land carbon uptake in this simulation. Thus to summarize the ZEC depends on both the thermal and bio-geochemical equilibration. The effect of thermal equilibration dominates in most simulations but for the last three $2 \times CO_2$ simulations the change in ocean heat uptake is the same and the change in bio-geochemical equilibration between the simulations dominates, which leads to an increase in the ZEC between these simulations.

Scenarios within each simulation set that differ in the timing of zeroing emissions also differ with regard to cumulative emissions (figures 1(*a*), 2(*a*)). Separating the effect of the state of equilibration and cumulative emissions is difficult. Previous studies [13, 15] that explored the warming commitment under different scenarios did not separate the effects of the total amount and the rate of emissions. Therefore, scenarios with higher cumulative emissions, linked to higher ZEC (at least for cumulative emissions above 2400 EgC), also entail higher emission rates and a stronger disequilibrium. Based on our current understanding of the coupled climate-carbon cycle system we expect that under higher cumulative emissions carbon sinks will be closer to saturation, which leads to lower $CO_2$ uptake. This lower $CO_2$ uptake entails lower cumulative emissions while atmospheric $CO_2$ is prescribed and a slower decline in atmospheric $CO_2$ once emissions are zeroed. The slower decline results in a higher ZEC. Thus, when only taking differences in cumulative emissions into account we would expect the ZEC to increase the later emissions are zeroed. However, ZEC are mostly deceasing the later emissions are zeroed suggesting that the effects of increased cumulative emission and bio-geochemical equilibration are less dominant than the effect of thermal equilibration. The sea level rise commitment is not affected by different cumulative

**Figure 5.** ZEC (*a*) and thermosteric sea level rise commitment (*b*) calculated as the change over 100, 400, 700, and 900 years after cessation of emissions.

emissions within each simulation set as the radiative forcing does not vary.

In addition to the time at which emissions are zeroed, the ZEC is also dependent on the $CO_2$ concentration scenario prior to zeroed emissions, which affects the state of equilibration, the radiative forcing, and cumulative emissions. For the $4 \times CO_2$ simulations the ZEC is 0.15 °C–0.86 °C whereas the $2 \times CO_2$ ZEC stays very low at 0.0 °C–0.10 °C (figure 4(*a*)). This large difference in ZEC can be explained with a lower realized warming fraction at the time of zeroed emissions under higher $CO_2$ concentration (figure 3(*a*)) and thus a stronger decline in ocean heat uptake. Furthermore, higher cumulative emissions together with climate carbon cycle feedbacks from increased temperatures due to increased radiative forcing lead to more saturated carbon sinks. This saturation entails a slower decline in $CO_2$ concentration after zeroing emissions and thus a larger ZEC. However, a higher $AF$ relative to its $AF_{eq}$ value for the $4 \times CO_2$ simulations compared to the $2 \times CO_2$ simulations at the time of zeroed emissions (figure 3(*b*)) indicates a lower state of bio-geochemical equilibration. This lower state of equilibration results in a stronger decline in $CO_2$ concentration leading to a lower ZEC. In total the effects of thermal equilibration and higher cumulative emissions dominate over the effect of bio-geochemical equilibration.

Thus far we have defined the ZEC between the time of zeroed emissions and 400 years after zeroed emissions. However, many studies differ in duration over which the commitment is calculated. Figure 5 shows warming and sea level rise commitments calculated as change over 100, 400, 700, and 900 years after cessation of emissions. This range of duration for calculating the commitment reflects the range in the existing literature [6, 11, 29]. Calculating ZEC only over 100 years for the $4 \times CO_2$ simulation gives significantly lower ZECs relative to the ZECs calculated over longer duration. For time horizons of 400 to 900 years the ZEC declines slightly for $2 \times CO_2$

simulations and increases slightly for $4 \times CO_2$ simulations the longer the time horizon over which the commitment is calculated whereas the sea level rise commitment increases significantly for both $4 \times CO_2$ and $2 \times CO_2$ simulations.

## 4. Discussion

A positive warming commitment for the UVic ESCM is consistent with other studies using the same model, as long as the emissions are positive prior to cessation of emissions [4, 14]. However, sign and magnitude of the warming commitment is highly model dependent [6, 7]. [11] suggest that EMICs have a negative ZEC and all ESM have a positive ZEC. We do not agree with this assessment, for the following three reasons. Firstly, there are ESMs that have negative ZEC in some studies [2, 5, 7, 10], depending on the scenario prior to setting emissions to zero, as discussed in section 1. Secondly, [11] compare their results with the warming commitment for the EMICs from [6], where slightly negative as opposed to zero emissions are prescribed, which leads to a low bias in the warming commitment for some EMICs as shown for the UVic ESCM (see supplementary material). Thirdly, consistent with other studies [4, 14] we show that the UVic ESCM, as an EMIC, has a positive ZEC. We caution against generalizing results to all EMICs, as this group of models is very heterogeneous (some are coarse resolution ESMs, whereas others are box models).

Most studies show small positive or negative ZECs (see section 1), which indicates that little additional warming after zeroed emissions needs to be taken into account when estimating the cumulative $CO_2$ emissions compatible with climate targets. Only studies using the ESM GFDL [11] find high ZECs under low warming scenarios (0.5 °C ZEC for 2 °C warming). Our analysis show a negligible warming commitment for $CO_2$ concentrations up to doubling of the pre-industrial $CO_2$ concentration or RCP4.5

concentrations after year 2200, whereas they show a significant warming commitment for quadrupling of pre-industrial concentrations or RCP8.5 concentrations after year 2200 (see supplementary material). An implication of this is that additional warming may not have to be considered for low climate targets (1.5 °C to 2 °C), whereas it may have to be considered for high targets.

## 5. Conclusions

In this study we investigate the effect of different factors on the zero emission warming commitment, including the effect of the state of thermal and bio-geochemical equilibration at the time emissions are set to zero, the $CO_2$ concentration level, and the time horizon over which the commitment is calculated. Previous studies have investigated the effect of thermal equilibration [11] but this study is the first one to our knowledge that investigates the effect of bio-geochemical equilibration as well. Both thermal and bio-geochemical equilibration have to be taken into account when discussing the ZEC as the commitment is determined by the warming effect from declining ocean heat uptake, associated with the state of thermal equilibration, and the cooling effect of declining atmospheric $CO_2$, which is affected by declining carbon uptake, and thus the state of bio-geochemical equilibration. The warming commitment is positive in all simulations, which implies that the warming effect of decline in ocean heat uptake dominates over the cooling effect of decline in atmospheric $CO_2$ and thus decline in radiative forcing.

Furthermore we find that the warming commitment declines the later emissions cease along a trajectory of constant atmospheric $CO_2$ concentration. This implies that the decrease in declining ocean heat uptake (decline in warming effect) dominates over the decrease in declining radiative forcing (decline in cooling effect). Thus the state of thermal equilibration, expressed as the realized warming fraction, has a stronger effect on the ZEC than the state of bio-geochemical equilibration, expressed as the ratio of airborne fraction to equilibrium airborne fraction. However, the warming commitment increases again once it declines to zero in the $2 \times CO_2$ simulations indicating the state of bio-geochemical equilibration dominates over the state of thermal equilibration in these cases. This behavior of the ZEC could be model dependent as the warming commitment in general is very model dependent as physical and bio-geochemical processes and their balance differ between models. Another factor that varies between simulations are the cumulative $CO_2$ emissions. Higher cumulative emissions for simulations with emissions zeroed later could lead to increasing ZEC or, rather, ZEC decreasing less if carbon sinks saturate. However, we expect this effect

to be small relative to the effect of thermal equilibration.

To summarize, the warming commitment is higher for higher $CO_2$ concentrations prior to cessation of emissions, the earlier emissions are zeroed in time, and the longer the duration over which the commitment is calculated. Whereas the first factor, the concentration prior to zeroed emissions, has a strong effect on the commitment, the time at which emissions are zeroed and the time period over which the commitment is calculated have only a small effect on the warming commitment. Thus, when comparing warming commitments from different studies we recommend only comparing studies with the same or similar scenarios prior to zeroed emissions whereas the other two factors might not have to be taken into account or could be adjusted by using our results. Furthermore, we find significant ZEC for high $CO_2$ concentration scenarios ($4 \times CO_2$ ZEC = 0.2 °C − 0.9 °C, RCP8.5 ZEC = 0.2 °C − 0.6 °C) but small ZECs for lower concentration scenarios ($2 \times CO_2$ ZEC = 0 °C − 0.1 °C, RCP4.5 ZEC = 0.07 °C − 0.2 °C). This implies that for low concentration scenarios no additional warming may need to be taken into account when estimating the cumulative $CO_2$ emissions compatible with climate targets, whereas additional warming may have to be considered for high concentration scenarios.

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