Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

| Citation | Zickfeld, Kirsten; Solomon, Susan and Gilford, Daniel M. “Centuries of Thermal Sea-Level Rise Due to Anthropogenic Emissions of Short-Lived Greenhouse Gases.” Proceedings of the National Academy of Sciences 114, no. 4 (January 2017): 657–662 © 2017 National Academy of Sciences |
| As Published | http://dx.doi.org/10.1073/pnas.1612066114 |
| Publisher | National Academy of Sciences (U.S.) |
| Version | Final published version |
| Accessed | Tue Feb 05 15:03:59 EST 2019 |
| Citable Link | http://hdl.handle.net/1721.1/109913 |
| Terms of Use | Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use. |
| Detailed Terms |  |
Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases

Kirsten Zickfeld\textsuperscript{a,1}, Susan Solomon\textsuperscript{b,1}, and Daniel M. Gilford\textsuperscript{b}

\textsuperscript{a}Department of Geography, Simon Fraser University, Burnaby, BC, Canada V5A 1S6; and \textsuperscript{b}Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307

Mitigation of anthropogenic greenhouse gases with short lifetimes (order of a year to decades) can contribute to limiting warming, but less attention has been paid to their impacts on longer-term sea-level rise. We show that short-lived greenhouse gases contribute to sea-level rise through thermal expansion (TSLR) over much longer time scales than their atmospheric lifetimes. For example, at least half of the TSLR due to increases in methane is expected to remain present for more than 200 y, even if anthropogenic emissions cease altogether, despite the 10-y atmospheric lifetime of this gas. Chlorofluorocarbons and hydrochlorofluorocarbons have already been phased out under the Montreal Protocol due to concerns about ozone depletion and provide an illustration of how emission reductions avoid multiple centuries of future TSLR. We examine the "world avoided" by the Montreal Protocol by showing that if these gases had instead been eliminated in 2050, additional TSLR of up to about 14 cm would be expected in the 21st century, with continuing contributions lasting more than 500 y. Emissions of the hydrofluorocarbon substitutes in the next half-century would also contribute to centuries of future TSLR. Consideration of the time scales of reversibility of TSLR due to short-lived substances provides insights into physical processes: sea-level rise is often assumed to follow air temperature, but this assumption holds only for TSLR when temperatures are increasing. We present a more complete formulation that is accurate even when atmospheric temperatures are stable or decreasing due to reductions in short-lived gases or net radiative forcing.

Significance

Human activities such as fossil-fuel burning have increased emissions of greenhouse gases (GHGs), which have warmed the Earth’s atmosphere and ocean and caused sea levels to rise. Some of these GHGs (e.g., methane) have atmospheric lifetimes of decades or less, whereas others (e.g., carbon dioxide) persist for centuries to millennia. As policy seeks to reduce climate changes, it is important to understand how mitigation of different gases each contributes to this goal. Our study shows that short-lived GHGs contribute to thermal expansion of the ocean over much longer time scales than their atmospheric lifetimes. Actions taken to reduce emissions of short-lived gases could mitigate centuries of additional future sea-level rise.

Author contributions: K.Z. and S.S. designed research; K.Z. and D.M.G. performed research; K.Z. and D.M.G. analyzed data; and K.Z., S.S., and D.M.G. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

\textsuperscript{1}To whom correspondence may be addressed. Email: kzickfel@sfu.ca or solos@mit.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1612066114/-/DCSupplemental.
with an atmospheric lifetime of about a decade, and it is the second largest contributor to global warming, after CO₂ (1).

Mitigation of CH₄ and other short-lived climate pollutants has been discussed as a way to reduce the risk of exceeding 2 °C of global warming (16), and it is reasonable to suggest that these pollutants may also be considered in pursuing efforts toward a more ambitious 1.5 °C target under the Paris agreement (15). Furthermore, the potential of mitigation of short-lived pollutants to reduce future sea-level rise has been highlighted (17). Here, we show that the TSLR from short-lived climate-forcing agents is much less reversible than their corresponding atmospheric warming, with effects that persist for centuries even after emissions stop. We explicitly consider the influences of CH₄ and HCs [including chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and perfluorinated gases] if their anthropogenic emissions were to cease. Although the CFCs are longer-lived than CH₄ or most HFCs, they are relatively short-lived compared with CO₂. We evaluate the continuing TSLR that is expected to occur due to the CFCs emitted to date, and we consider how much future TSLR has been avoided due to the Montreal Protocol, which has phased out production of these compounds. We use a state-of-the-art EMIC, the University of Victoria Earth System Climate Model (UVic ESCM) (Methods).

A number of studies have developed empirical relationships between sea-level rise and atmospheric warming (18, 19), but less work has examined these relationships when the atmospheric temperature is cooling or constant. Bouttes et al. (3) developed a relationship between sea-level rise and radiative forcing (RF) rather than atmospheric warming. Here, we build on the work of Bouttes et al. to develop a framework for understanding TSLR that is valid regardless of whether atmospheric temperatures are decreasing or increasing and show the framework’s value for understanding relevant physics.

Results and Discussion

Dependence on GHG. Fig. 1 shows the model-calculated temperature and TSLR response to past and future anthropogenic emissions of CO₂, CH₄, N₂O, and HCs. We use a high-emission scenario (RCP8.5) to year 2050 and zero anthropogenic emissions of these gases thereafter (Methods). When emissions are set to zero, atmospheric CO₂ starts to decline. On decadal time scales, the decline in atmospheric CO₂ is governed by CO₂ uptake by the land carbon sink and dissolution and buffering of CO₂ in the ocean mixed layer. Saturation of these sinks leads to slowing of the CO₂ decline after a few decades, as seen in Fig. 1A. On centennial time scales, atmospheric CO₂ uptake is controlled by buffering of CO₂ in the deep ocean, whereas on millennial time scales, the dominant process is dissolution of CaCO₃ in sediments, which restores the ocean’s buffer capacity (20). In our simulation, about 50% of the total emitted CO₂ remains in the atmosphere 750 y after emissions cease. The persistence of the CO₂ perturbation is dependent on the magnitude of the CO₂ emission, with larger CO₂ perturbations persisting longer (8), and the strength of climate-carbon cycle feedbacks in the model. An EMIC intercomparison shows that in the UVic ESCM, the fraction of excess CO₂ remaining in the atmosphere after 100 y is close to the model mean, whereas the fraction remaining after 1,000 y is at the upper end of the model range for emission pulses of both 100 and 5,000 gigatons of carbon (21).

Removal of N₂O, CH₄, and HCs from the atmosphere and the associated decline in RF (Fig. 1B) is much faster than that for CO₂. Removal of these gases is controlled by well-known chemical reactions in the atmosphere and follows an exponential decline with a single time constant, which corresponds to the atmospheric lifetime of the gas [about a decade for CH₄ and 120 y for N₂O (22)]. For CO₂ and CH₄, the decline in RF as concentrations decrease is delayed because the radiative effects of these gases are not optically thin, yielding a nonlinear relationship between atmospheric concentration and RF (2). N₂O and HCs, on the other hand, are optically thin, and the decline in RF is more linear with concentration. The TSLR that occurs due to these gases is therefore much more reversible than the TSLR from CO₂, and the TSLR from CH₄ is even more reversible than the TSLR from N₂O and HCs. The TSLR from CH₄ is also much larger than the TSLR from N₂O and HCs, even though CH₄ is less efficient at warming the atmosphere than N₂O and HCs. This is because CH₄ has a longer atmospheric lifetime than N₂O and HCs, and the longer the lifetime of a gas, the more it contributes to future warming.

In conclusion, the TSLR from short-lived climate-forcing agents is much less reversible than their corresponding atmospheric warming, with effects that persist for centuries even after emissions stop. This highlights the need for continued efforts to mitigate these short-lived climate pollutants and for the development of robust frameworks for understanding their contributions to future sea-level rise.
hand, are optically thin and do not display nonlinear spectral effects. Lifetimes of HCs span a wide range from a year or a few decades for many HFCs and HCFCs, to 50–100 y for CFCs and tens of thousands of years for perfluorocarbons such as CF4 (22). Due to these long-lived gases, 0.02 W/m² HC RF (corresponding to 6% of the peak HC RF in RCP 8.5) persists for over 1,000 y.

Fig. 1C shows that surface-air warming remains approximately constant for 1,000 y after elimination of CO2 emissions. The warming contribution from N2O, HCs, and CH4 decays more quickly than that from CO2, but more slowly than what would be expected based simply on the atmospheric lifetime of these gases (2). One hundred years after emissions cease, 71% of the peak warming still persists for N2O, 41% for HCs, and 13% for CH4. The persistence of the warming is due to ocean thermal inertia: when GHG emissions stop the system is not yet equilibrated with the peak RF and the ocean continues to take up heat. However, it is important to note that as RF declines, the energy imbalance at the top of the atmosphere is reduced. Further, the amount of heat taken up by the ocean diminishes, which has a warming effect on the atmosphere and slows the cooling associated with the decline in RF. For CO2, this RF decline is so slow that it very nearly compensates for the warming effect due to ocean thermal inertia, resulting in a net warming that is largely irreversible for at least 1,000 y (7, 8).

TSLR due to anthropogenic CO2 continues to increase after the elimination of CO2 emissions. TSLR is estimated at about twice the year-2050 value 100 y after CO2 emissions cease and almost four times that value 500 y after emissions cease; this continued TSLR is due to the long equilibration time scale of the ocean. Further, the amount of heat uptake per degree surface air warming) of Climate Model Intercomparison Project 5 (CMIP5) models (28). This scaling gives a TSLR range of 1.2–3.7 and 4.5–14 cm for world-avoided scenarios with HC RF zeroed in 2015 and 2050, respectively. Note that because of the high ocean heat-uptake efficiency of the UVic ESCM, the TSLR estimates presented in this study are at the upper end of this range.

Our results indicate that future emissions of non-ozone-depleting HCs can be expected to make a relatively small but persistent contribution to higher sea levels for several centuries even if their emissions were to stop. A recent policy decision is directed at phasing down HFC emissions through the Montreal Protocol (see technical discussion in ref. 23). We next examine the TSLR contribution from HCs if policies to phase down the consumption of HFCs were to be implemented using the “Phasedown” scenario developed by Rigby et al. (23), whereby overall HC RF decreases from 0.35 Wm⁻² in 2012 to 0.26 Wm⁻² in 2050, compared with a more modest decrease to 0.31 Wm⁻² in 2050 under RCP8.5 (Fig. 2). We compare these thermal expansion contributions to two “no-HFC policy” scenarios, RCP8.5 and the high-end HC RF scenario discussed in Velders et al. (24); referred to as “Velders-high” (year-2050 RF of 0.49 W/m²). As in the simulations described previously, HC RF follows these scenarios to 2050, after which emissions of all gases are eliminated. By year 2550 (500 y after emissions stop), TSLR due to HCs is similar across scenarios, indicating that by that time, the effect of HC policies is small (<0.3 cm).

An interesting question is how ocean thermal expansion would have evolved had the ozone-depleting CFCs and HCFCs not been phased out under the Montreal Protocol. Such “world-avoided” scenarios have been explored for ozone depletion, RF, and surface temperature by several groups (e.g., refs. 25–27), but previous studies have not investigated the effect on TSLR. Here, we force the UVic ESCM using a scenario with RF from ozone-depleting substances (including CFCs, CH3CCl3, and CCl4) growing at an adopted rate of 4% per year (about the growth rate in the 1980s) after the late 1980s [when the Montreal Protocol was signed and entered into force (23)]. We hold the RF of HFCs, HCFCs, and perfluorocarbons constant at year-1989 levels because several of these gases were phased in as substitutes for CFCs. Emissions of all HCs are then set to zero in year 2015 or 2050. In these two world-avoided scenarios, HC RF reaches peak values of 0.71 W/m² in 2015 and 2.7 W/m² in 2050, respectively, compared with a peak value of 0.35 W/m² in the reference RCP8.5 scenario. This RF results in additional peak warming relative to the year 1800 of 0.3 °C and 1.3 °C, respectively (RCP8.5: 0.2 °C). Additional TSLR is 3.7 and 13.8 cm by 2100, respectively, and continuing contributions occur for centuries thereafter. The UVic ESCM overestimates ocean heat uptake over the historical period and is at the higher end of the range of ocean heat uptake (and hence TSLR) projections spanned by EMICs (9). To quantify the uncertainty in the TSLR rise estimates given above, we scale these estimates with the ocean heat-uptake efficiencies (defined as ocean heat uptake per degree surface air warming) of Climate Model Intercomparison Project 5 (CMIP5) models (28). This scaling gives a TSLR range of 1.2–3.7 and 4.5–14 cm for world-avoided scenarios with HC RF zeroed in 2015 and 2050, respectively. Note that because of the high ocean heat-uptake efficiency of the UVic ESCM, the TSLR estimates presented in this study are at the upper end of this range.

![Fig. 2. Climate response for scenarios with high (Velders-high), medium (RCP8.5), and low (Phasedown) HC (includes HFC, HCFC, CFC, and perfluorocarbon) RF to 2050 and exponentially declining RF thereafter. Results are also shown for two world-avoided scenarios with RF of ozone-depleting substances increasing at 4% per year (the increase rate before implementation of the Montreal Protocol) to 2015 and 2050 and zero emissions thereafter. The response to HC forcing is calculated as the difference between CO2 + N2O + CH4 + HC and CO2 + N2O + CH4 simulations. (A) HC RF. (B) SAT difference. (C) Ocean thermal expansion difference.](https://example.com/fig2.png)
**Dependence on Emission Scenario.** In the following, we further examine the dependence of the warming and TSLR commitment on the emissions scenario for a GHG with a very long (millennial) atmospheric lifetime (CO₂) and one with a relatively short lifetime (CH₄). We explore the climate response to emission scenarios following RCP8.5 to year 2050, 2100, and 2150 and zero emissions thereafter for a case with CO₂ emissions only and one with CO₂ and CH₄ emissions. The climate response to CH₄ (Fig. 3) is calculated as the difference between the CO₂ + CH₄ and CO₂-only cases.

These experiments demonstrate the critical importance of earlier actions if future warming and sea-level rise are to be limited. For CO₂, the longer emissions are sustained, the larger the fraction of total emissions remaining in the atmosphere 500 y after emissions are set to zero (Fig. S2) (6, 8). SAT continues to increase after CO₂ emissions cease, with the warming “commitment” increasing if emissions are sustained longer (9). The thermal expansion commitment also increases for scenarios with longer sustained CO₂ emissions.

For CH₄, the fraction of RF persisting at a given time after emissions are zeroed is the same for all scenarios (by definition) (Fig. 3). The SAT decline is also very similar between scenarios, with 14–17% of the peak warming remaining 100 y after emissions cease. The decline in thermal expansion, on the other hand, is emissions scenario-dependent: the longer emissions follow RCP8.5 before they are set to zero, the larger the TSLR persisting at any given time. In relative terms, the thermal expansion persisting 200 y after emissions are set to zero is 60, 53, and 54% of the peak for scenarios with emissions set to zero in 2050, 2100, and 2150, respectively. Interestingly, the fraction of the peak TSLR persisting is largest in the scenario with the lowest duration/total amount of emissions. We attribute these differences in the timing of heat release to differences in the Atlantic Meridional Overturning Circulation (AMOC) in the climate state from which the CH₄ forcing is applied (recall that the three scenarios also differ in terms of atmospheric CO₂ concentration; Fig. S2A). For scenarios with longer sustained GHG emissions, the AMOC weakens more in this model, resulting in less heat being mixed into the deep ocean during periods of increasing RF but also allowing for a faster release of the heat during periods of declining RF.

Ocean heat uptake and release at a given time is set by the time scale of mixing of heat into/out of the deep ocean, which is dependent on a model’s mixing parameterization and ocean circulation response. Both differ widely between models. In particular, the ability of EMICs to correctly simulate the time scale of ocean heat uptake has been questioned (29). Fig. S3 compares the surface air and ocean temperature (a proxy for TSLR) responses of the UVic ESCM to those of the Hadley Centre Earth System Model (HadGEM2) for a set of idealized scenarios with a 1% per year CO₂ increase followed by a 1% per year decrease (30, 31). We find that the time scales of surface air and ocean-temperature response to rapidly declining CO₂ forcing are very similar between the two models, suggesting that the centennial time scale of TSLR reversibility for short-lived GHGs found in this study is robust across models of different complexity.

Given concerns about challenges and progress in limiting emissions of CO₂ at a global scale, and the longevity of CO₂ in the atmosphere, technologies that seek to remove CO₂ artificially from the atmosphere have been discussed (32). Artificial carbon dioxide removal (referred to as “CDR”) would lead to a faster decline in CO₂ RF, potentially allowing for the reversal of CO₂-induced climate change and return to a given climate target (such as the 1.5 and 2 °C goals included in the Paris Agreement) after overshoot. The results presented here for short-lived climate forcers indicate that although CDR could be effective at restoring global SAT to a target level within decades, it would take centuries to reverse the associated thermal expansion (33).

**Physical Processes That Determine Rate of Thermal Expansion.** We next develop a simple model to explore the TSLR response during periods of declining RF. It has been suggested that thermal expansion in response to increasing RF is approximately proportional to the time-integrated RF (3), which in turn can be used to justify empirical approaches that assume the rate of sea-level rise to scale with atmospheric temperature anomaly (18, 19). Empirical formulations have the advantages of simplicity and consideration of ice loss along with thermal expansion. However, here, we show that additional information is needed to capture the thermal expansion during periods of strongly declining RF, as is the case for CH₄ after elimination of emissions: time-integrated RF approaches a constant level shortly after emissions cease, but rather than remaining constant, modeled thermal expansion declines significantly after emissions stop in all scenarios (Fig. 3). We expand the formulation of Bouttes et al. (3) by introducing an additional term to include the important effect of radiative damping through energy loss to space:

$$\eta = \alpha \int RF \, dt - \beta \int (T - T_0) \, dt,$$

where \(\eta\) is ocean thermal expansion, \(RF\) is total RF (in W/m²), \(\Delta T = T - T_0\) is the temperature anomaly relative to a reference year (denoted year 0), and \(\alpha, \beta\) are constants (see below).

**Fig. 3.** Climate response computed with the UVic ESCM for scenarios with CH₄ emissions following RCP8.5 to year 2050, 2100, 2150, and zero anthropogenic emissions (ZE) thereafter. Variables are calculated as differences between CO₂ + CH₄ and CO₂-only simulations and are aligned at the time emissions are set to zero (which results in a shift by 50 and 100 y in the ZE2100 and ZE2150 scenarios, respectively). (A) CH₄ RF. (B) SAT anomaly relative to year 1800. (C) Ocean thermal expansion relative to year 1800.
By taking the time derivative, one obtains a useful expression for the rate of TSLR:

$$\frac{d\eta}{dt} = \alpha \Delta T - \beta \Delta T. \quad [2]$$

The ratio $\beta/\alpha$ has units of W m$^{-2}$ K$^{-1}$, the same units as the climate-feedback parameter (denoted as $\lambda$). The equivalence between the ratio $\beta/\alpha$ and the climate-feedback parameter can easily be seen by assuming that the rate of thermal expansion is proportional to the rate of ocean heat-uptake $N (dN/dt = \gamma N$, where $\gamma$ is a proportionality constant) and comparing the resulting expression to a zero-dimensional global Earth energy balance model:

$$N = RF - \lambda \Delta T. \quad [3]$$

Using this simple energy balance model and assuming a representative value of $\lambda$ allows one to directly predict the evolution of TSLR for given climate scenarios, including those where RF is strongly decreasing.

The TSLR predicted by the simple model given in Eq. 2 agrees well with the thermal expansion simulated by the UVic ESCM during periods of both increasing and decreasing RF, as illustrated in Fig. 4 for the scenario with zero emissions after year 2100. Analysis of the terms in Eq. 3 gives insight into the different thermal expansion responses to CO$_2$ and CH$_4$ RF (Fig. 4A and C). For CO$_2$, RF declines after emissions are set to zero, whereas SAT and hence radiative damping ($\lambda \Delta T$) continues to increase slightly; RF remains larger than $\lambda \Delta T$ for CO$_2$ in Fig. 4A, although the difference declines toward the end of the simulation. Therefore, the rate of thermal expansion remains positive after emissions cease, and the expansion declines over time (Fig. 4B). For CH$_4$, RF declines rapidly after emissions are set to zero (reflecting the short residence time of CH$_4$), SAT lags the decline in RF but also decreases. The net result is that RF becomes smaller than $\lambda \Delta T$ shortly after emissions cease, such that the rate of thermal expansion becomes negative (Fig. 4C and D). These physical principles demonstrate why geoengineering proposals that could decrease atmospheric temperature to a target level within decades, such as CDR or solar radiation management schemes, would also imply a much slower decline in sea level (33).

Bouttes et al. (3) also considered a zero-dimensional energy balance model (Eq. 2), but their formulation does not include the thermal expansion response during periods of declining RF. The reason is that they assumed the rate of ocean heat-uptake $N$ is always proportional to temperature ($N = \kappa \Delta T$, where $\kappa$ is the ocean heat-uptake efficiency). This linear assumption is justified for increasing but not for decreasing RF, when $N$ can become negative.

Observational constraints on sea-level rise using historical data have been tested in previous studies (e.g., refs. 34 and 35) with paleoclimate records. However, these semiempirical approaches were calibrated assuming sea-level rise will tend toward its long-term (multimillennial) global temperature relationship in the presence of short-term forcing; they do not include a forcing term based on Earth’s energy balance, and they have not been tested under periods of sharply declining RF (such as those that occur if CH$_4$ emissions suddenly cease). Our method is valuable because it is generalizable for any climate scenario and model given the value of $\lambda$, which allows us to separate the physical contributions to TSLR from energy input to the ocean and radiative damping.

**Conclusions**

We have used an EMIC to elucidate thermal sea-level responses to changes in short-lived GHGs and have described the responses’ contrasts and similarities with those obtained for CO$_2$. We have only considered thermal sea-level rise and have neglected contributions from glaciers and ice-sheet melt. On very long (>1,000 y) time scales, these processes are expected to dominate contributions to the global GHG commitment to sea-level rise, and the relationship between ice-melt contributions and thermal expansion is only quasilinear (34).

Our results show that centuries of TSLR are to be expected if the emissions of CH$_4$ or other short-lived anthropogenic GHGs such as HFCs were to cease, due to the slow time scales of release...
of heat from the atmosphere/ocean system. Thus, although sea-level rise due to short-lived GHGs can be expected to become small compared with CO$_2$'s influence on sea level within a few hundred years if anthropogenic emissions of both were to cease, the climate impacts of short-lived GHGs are far longer-lasting than would be implied by their atmospheric lifetimes alone. A simple energy balance model has been used to elucidate the factors that influence the rate and magnitude of sea-level rise regardless of whether RF and atmospheric temperatures are increasing or decreasing. This study shows that radiative damping and ocean heat uptake are important in determining the temporal evolution of sea-level rise and that the rate of sea-level rise can be readily related to the climate-feedback parameter.

CFCs, HCFCs, and HFCs are much shorter-lived than CO$_2$ and yet cause sea-level rise that also persists for centuries. We have shown that choices made to phase out the CFCs and HCFCs during the 20th century under the Montreal Protocol have avoided a considerable amount of TSLR. If the CFCs and HCFCs had not been phased out until 2050, an additional 13.8 cm (4.5–14.0 cm) of TSLR would be expected by the end of this century, with continuing contributions for many centuries to come; this finding attests to the long-term value of the Montreal Protocol in avoiding a world with significantly higher sea levels.

The primary policy conclusion of this study is that the long-lasting nature of sea-level rise heightens the importance of earlier mitigation actions—even in the case of a short-lived substance such as CH$_4$, HFCs, etc. Our work also indicates that longer-term sea-level rise impacts should be considered if the climate implications of geoengineering proposals that seek to reduce RF or atmospheric temperatures are to be fully evaluated. As can be seen in Fig. 3 for CH$_4$, a scenario that reduces atmospheric temperature cannot be assumed to simultaneously eliminate future sea-level rise, due to the time scales associated with release of stored energy in the ocean.

**Methods**

We use version 2.9 of the UVic ESM (B, 36), a model of intermediate complexity. This version of the UVic ESM includes a 3D ocean GCM, coupled to a dynamic-thermodynamic sea-ice model and a single-layer energy–moisture balance model of the atmosphere with dynamical feedbacks. The physical climate model is fully coupled to carbon-cycle components on land and in the ocean. Further details regarding the model and simulation protocol are provided in SI Methods.

**ACKNOWLEDGMENTS.** We thank W. Morgenstern for preparing the RF input and carrying out part of the model simulations with the UVic ESM. This research was enabled in part by computing resources provided by Westgrid and Compute Canada. K.Z. acknowledges support from the Natural Sciences and Engineering Research Council of Canada Discovery Grant and Undergraduate Student Research Assistant Programs. D.M.G. is partly supported by a National Aeronautics and Space Administration fellowship.

Supporting Information

Zickfeld et al. 10.1073/pnas.1612066114

SI Methods

We use version 2.9 of the UVic ESCM (8, 36), a model of intermediate complexity with a horizontal grid resolution of 1.8° × 3.6°. This version of the UVic ESCM includes a 3D ocean GCM with isopycnal mixing and a Gent–McWilliams parameterization of the effect of eddy-induced tracer transport. For diapycnal mixing, a Bryan and Lewis profile of diffusivity is applied, with a value of 0.3 × 10^{-4} m^2 s^{-1} in the pycnocline. The ocean model is coupled to a dynamic–thermodynamic sea-ice model and a single-layer energy–moisture balance model of the atmosphere with dynamical feedbacks (36). The atmospheric model does not simulate clouds, and precipitation is assumed to occur when relative humidity exceeds 85%. The model includes a parameterization of water vapor/planetary longwave feedbacks, and the RF associated with changes in atmospheric CO\textsubscript{2} and other GHGs is prescribed as a modification of the planetary longwave radiative flux. The land surface and vegetation are represented by a simplified version of the Hadley Centre’s land-surface scheme (Met Office Surface Exchange Scheme) coupled to the dynamic vegetation model TRIFFID (Top-Down Representation of Interactive Foliage and Flora Including Dynamics). Ocean carbon is simulated by means of an Ocean–Carbon Cycle Model Intercomparison Project-type inorganic carbon-cycle model and a marine ecosystem/biogeochemistry model solving prognostic equations for nutrients, phytoplankton, zooplankton, and detritus. The version of the UVic ESCM used here includes a marine sediment component (8). CO\textsubscript{2} can be specified to the model either in terms of emissions or atmospheric concentrations. The model does not include an atmospheric chemistry module; non-CO\textsubscript{2} GHGs are specified as RF.

The UVic ESCM took part in numerous model intercomparison projects, including the EMIC Intercomparison in support of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (EMIC AR5) (9, 37). The model’s standard climate sensitivity is 3.5 °C for a doubling of the preindustrial atmospheric CO\textsubscript{2} concentration (37). The model overestimates thermal sea-level rise over the historical period and is at the higher end of the range of thermal sea-level rise projections spanned by EMICs (9). In terms of carbon cycle response to CO\textsubscript{2} and climate change, the UVic ESCM lies in the middle of the range of responses of EMICs and complex Earth system models (37, 38).

Several simulations were run with the UVic ESCM, with different combinations of GHGs and different times at which GHG emissions were set to zero. These simulations were initialized from a preindustrial equilibrium state of the model. CO\textsubscript{2}-only simulations were forced with historical CO\textsubscript{2} concentrations to 2010 and RCP8.5 and ECP8.5 CO\textsubscript{2} concentrations from 2010 to 2300 (39). CO\textsubscript{2} emissions were then set to zero at different times along this trajectory: in 2050, 2100, and 2150. CO\textsubscript{2} concentrations from these simulations were used to force runs with different combinations of non-CO\textsubscript{2} forcings: CH\textsubscript{4}, CH\textsubscript{4} + N\textsubscript{2}O and CH\textsubscript{4} + N\textsubscript{2}O + HCs. HCs here include CFCs, HCFCs, HFCs, and perfluorinated gases. RF of CH\textsubscript{4} and N\textsubscript{2}O followed observation-based values to 2010 and RCP8.5 and ECP8.5 values thereafter. The decline in RF after emissions of these gases were set to zero was calculated using standard formulae (see, for example, supplementary material 8.SM.3 of ref. 22). For HCs, we used observations-based RF to 2010 [Advanced Global Atmospheric Gases Experiment (40)] and three different RF scenarios up to 2050 spanning a range of plausible future emissions of these gases: a high scenario from Velders et al. (24) (“Velders-high”), a medium scenario (RCP8.5), and a low scenario proposed by Rigby et al. (23), which assumes that policies to phase down the consumption of HFCs are implemented (Phasedown). After 2050, HC RF was prescribed to decline exponentially according to each gas’s atmospheric lifetime as given in appendix 8.A of ref. 22. In addition, we forced the model with two world-avoided scenarios, whereby RF of ozone depleting substances (CFCs, CH\textsubscript{3}CCl\textsubscript{3}, and CCl\textsubscript{4}) increases at 4% per year (the rate of increase in the 1980s before ratification of the Montreal Protocol), and RF of HFCs and HCFCs is held constant at year-1998 levels. Emissions of these gases are assumed to stop after 2015 or 2050 and RF to decline exponentially. This simulation also includes RF from CO\textsubscript{2}, CH\textsubscript{4}, and N\textsubscript{2}O evolving as in the year-2050 zero emissions simulation described above.
Fig. S1. Linearity of SAT (A) and thermal sea-level-rise (B) responses associated with CH4 emissions. CH4-induced responses are diagnosed from simulations with CH4 RF applied in isolation or from differences between simulations with different combinations of GHGs. Results are shown for a scenario with emissions following RCP8.5 to year 2050, with zero anthropogenic emissions thereafter (ZE2050). TSLR is slightly larger and takes slightly longer to reverse if CH4 is emitted in isolation, than if it is emitted simultaneously with CO2, which has a much larger RF (Fig. S2). This difference in TSLR is due to differences in ocean heat uptake at low and high RF: when only CH4 is emitted, the ocean is less stratified and more heat is taken up, resulting in a slightly lower SAT and slightly larger thermal expansion.

Fig. S2. Climate response computed with the UVic ESCM for a scenario with emissions of CO2 and CH4, following RCP8.5 to year 2050, 2100, 2150, and with zero anthropogenic emissions (ZE) thereafter. (A) Atmospheric CO2 concentration. (B) SAT anomaly relative to year 1800. (C) Ocean thermal expansion relative to year 1800. (D) Total RF. (E) Rate of SAT change. (F) Rate of ocean thermal expansion. Solid lines refer CO2-only simulations; dashed lines refer to CO2 + CH4 simulations.
Fig. S3. Comparison of SAT (Top) and ocean-temperature (Bottom) response for the UVic ESCM (dashed lines) and the HadGEM2 ESM (solid lines). Results are shown for idealized scenarios with a 1% per year increase in atmospheric CO$_2$ ("ramp up"), followed by a 1% per year CO$_2$ decrease ("ramp down") from 2× CO$_2$, 3× CO$_2$, and 4× CO$_2$ (1, 2). For better comparison of the response time scales involved, temperature anomalies are normalized to the peak value in the respective model.