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

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Edited by Veerabhadran Ramanathan, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, and approved December 13, 2016 (received for review July 21, 2016)

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.

climate change | sea-level rise | greenhouse gases | reversibility | Montreal Protocol

Atmospheric concentrations of a range of greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons (HCs), have increased since the beginning of the industrial revolution and have been the main drivers of warming global air and ocean temperatures as well as rising sea levels (1). The goal of this paper is to assess whether the sea-level rise through thermal expansion (TSLR) induced by anthropogenic increases in GHGs that are short-lived (i.e., those with atmospheric residence times of years to decades) is reversible, and on what time scales (2, 3). We also discuss the TSLR due to long-lived gases (defined here as those with residence times of several centuries or longer) and show how the comparison of responses of TSLR to different gases elucidates the climate-system processes that control TSLR reversibility. Understanding how emissions of different gases each affect the Earth's climate over time is central to policy evaluation (e.g., when tradeoffs between mitigation options for different GHGs are considered).

A fundamental goal of the United Nations Framework Convention on Climate Change (UNFCCC) and its Paris agreement is the stabilization of GHGs at a level that would avoid dangerous anthropogenic interference with the climate system. Future emission pathways that would lead to stabilized concentrations of anthropogenic GHGs, and the attendant consequences for global warming and sea-level rise, have been examined with a wide range of approaches, including models and semiempirical studies (1). Commitments to further changes in air temperatures and TSLR even after stabilization of CO_2 and other forcing agents have also been estimated (1). In addition to stabilization, the "potentially irreversible threat to human societies and the planet" (ref. 4, p. 1) from climate changes is important in assessing risk, and both stabilization and irreversibility are cornerstones of the UNFCCC and Paris agreements (4).

Recent studies by many different groups have shown that the atmospheric warming due to anthropogenic CO_2 emissions is expected to remain nearly constant for more than a millennium, even if manmade emissions were to stop entirely, so that this climate change is essentially irreversible on human time scales. Whereas atmospheric temperatures remain approximately constant, the associated TSLR is expected to continue to increase for centuries even after emissions cease, based on both Earth system models of intermediate complexity (EMICs) (5–9) and general circulation model (GCM)-based Earth system models (10–13). Note that in this paper, we do not evaluate hypothetical geoengineering measures that may be able to remove gases from the atmosphere or induce active atmospheric cooling to counter warming. However, our results are relevant to understanding how TSLR should be expected to respond even if such measures were eventually able to safely and effectively produce net atmospheric cooling, as discussed below.

In contrast to the irreversible climate impacts of CO_2 emissions, the atmospheric warming impact of short-lived climate pollutants can in principle be reversed on time scales of decades if anthropogenic emissions were to decrease or cease (14–16). The most abundant short-lived climate-forcing agent is CH_4,

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.

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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 CO_2 (1).

Mitigation of CH_4 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 CH_4 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 CH_4 or most HFCs, they are relatively short-lived compared with CO_2. 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 CO_2, CH_4, N_2O, 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 CO_2 starts to decline. On decadal time scales, the decline in atmospheric CO_2 is governed by CO_2 uptake by the land carbon sink and dissolution and buffering of CO_2 in the ocean mixed layer. Saturation of these sinks leads to slowing of the CO_2 decline after a few decades, as seen in Fig. 1*A*. On centennial time scales, atmospheric CO_2 uptake is controlled by buffering of CO_2 in the deep ocean, whereas on millennial time scales, the dominant process is dissolution of $CaCO_3$ in sediments, which restores the ocean's buffer capacity (20). In our simulation, about 50% of the total emitted CO_2 remains in the atmosphere 750 y after emissions cease. The persistence of the CO_2 perturbation is dependent on the magnitude of the CO_2 emission, with larger CO_2 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 CO_2 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 N_2O, CH_4, and HCs from the atmosphere and the associated decline in RF (Fig. 1*B*) is much faster than that for CO_2. 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 CH_4 and 120 y for N_2O (22)]. For CO_2 and CH_4, 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). N_2O and HCs, on the other

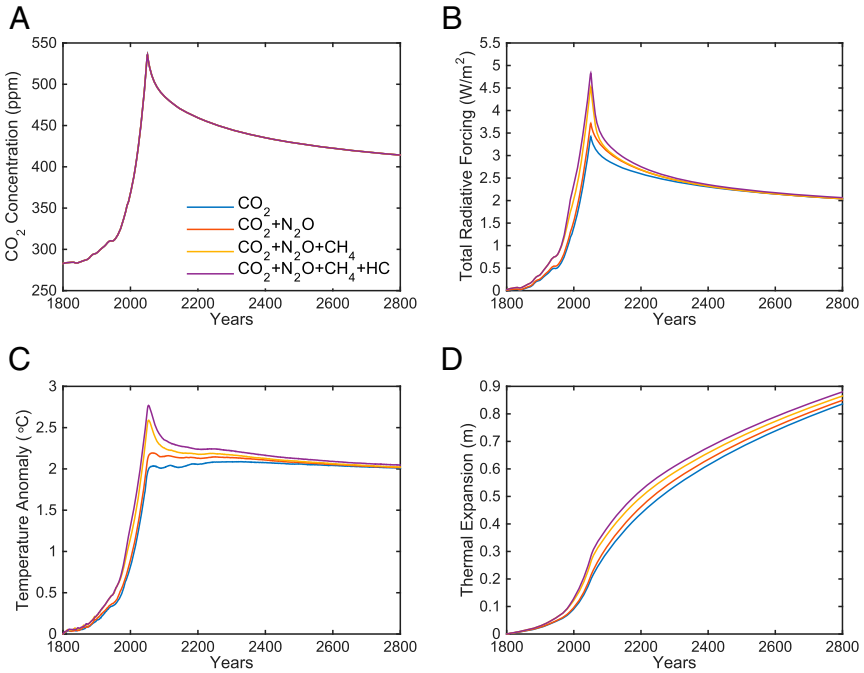

Fig. 1. Climate response computed with the UVic ESCM for a scenario with emissions of CO_2, CH_4, N_2O, and HCs (including CFCs, HFCs, HCFCs, and perfluorocarbons) following RCP8.5 to year 2050 and zero anthropogenic emissions thereafter. (*A*) Atmospheric CO_2 concentration. (*B*) Total RF. (*C*) SAT anomaly relative to year 1800. (*D*) Ocean thermal expansion relative to year 1800. GHGs are changed sequentially in the model simulations to isolate the contributions of each gas.

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 CF_4 (22). Due to these long-lived gases, 0.02 W/m^2 HC RF (corresponding to 6% of the peak HC RF in RCP 8.5) persists for over 1,000 y.

Fig. 1*C* shows that surface-air warming remains approximately constant for 1,000 y after elimination of CO_2 emissions. The warming contribution from N_2O, HCs and CH_4 decays more quickly than that from CO_2, 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 N_2O, 41% for HCs and 13% for CH_4. The persistence of the warming is due to ocean thermal inertia: when GHG emissions stop the system is still not 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 CO_2, 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 CO_2 continues to increase after the elimination of CO_2 emissions. TSLR is estimated at about twice the year-2050 value 100 y after CO_2 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 deep ocean as noted above. TSLR linked to N_2O, CH_4 and HCs starts to decline soon after their emissions are eliminated, but Fig. 1*D* shows that these impacts decay far more slowly than their respective warming contributions. For example, 75% of the peak thermal expansion persists 100 y after CH_4 emissions are set to zero and close to 40% persists 500 y after emissions are set to zero. We tested the linearity of the surface-air temperature (SAT) and TSLR response when combining the RF from different GHGs. Although there is a small difference in the TSLR response to a short-lived gas depending on whether the gas is emitted simultaneously with CO_2 or in isolation, the response is largely insensitive to the order in which these gases are added to CO_2 (Fig. S1).

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*A*). 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/m^2). 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 HFC 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, CH_3CCl_3, and CCl_4) 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/m^2 in 2015 and 2.7 W/m^2 in 2050, respectively, compared with a peak value of 0.35 W/m^2 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.

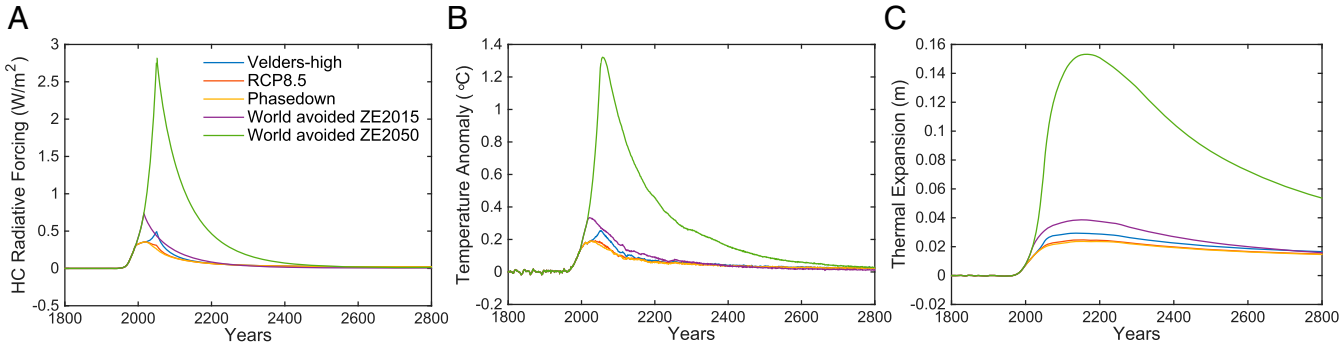

Fig. 2. Climate response for scenarios with high (Velders-high), medium (RCP8.5), and low (Phasedown) HC (includes HFC, HCFC, CFC, and perfluorocarbon) RF to 2050 and exponentially declining RF thereafter. Results are also shown for two world-avoided scenarios with RF of ozone-depleting substances increasing 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 $CO_2 + N_2O + CH_4 + HC$ and $CO_2 + N_2O + CH_4$ simulations. (*A*) HC RF. (*B*) SAT difference. (*C*) Ocean thermal expansion difference.

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 (CO_2) and one with a relatively short lifetime (CH_4). 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 CO_2 emissions only and one with CO_2 and CH_4 emissions. The climate response to CH_4 (Fig. 3) is calculated as the difference between the CO_2 + CH_4 and CO_2-only cases.

These experiments demonstrate the critical importance of earlier actions if future warming and sea-level rise are to be limited. For CO_2, 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 CO_2 emissions cease, with the warming "commitment" increasing if emissions are sustained longer (9). The thermal expansion commitment also increases for scenarios with longer sustained CO_2 emissions.

For CH_4, 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 CH_4 forcing is applied (recall that the three scenarios also differ in terms of atmospheric CO_2 concentration; Fig. S2*A*). 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 CO_2 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 CO_2 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 CO_2 at a global scale, and the longevity of CO_2 in the atmosphere, technologies that seek to remove CO_2 artificially from the atmosphere have been discussed (32). Artificial carbon dioxide removal (referred to as "CDR") would lead to a faster decline in CO_2 RF, potentially allowing for the reversal of CO_2-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 CH_4 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:

$$\eta = \alpha \int RF\, dt - \beta \int (T - T_0) dt, \qquad [1]$$

where η is ocean thermal expansion, RF is total RF (in W/m^2), $\Delta T = T - T_0$ is the temperature anomaly relative to a reference year (denoted year 0), and α, β are constants (see below).

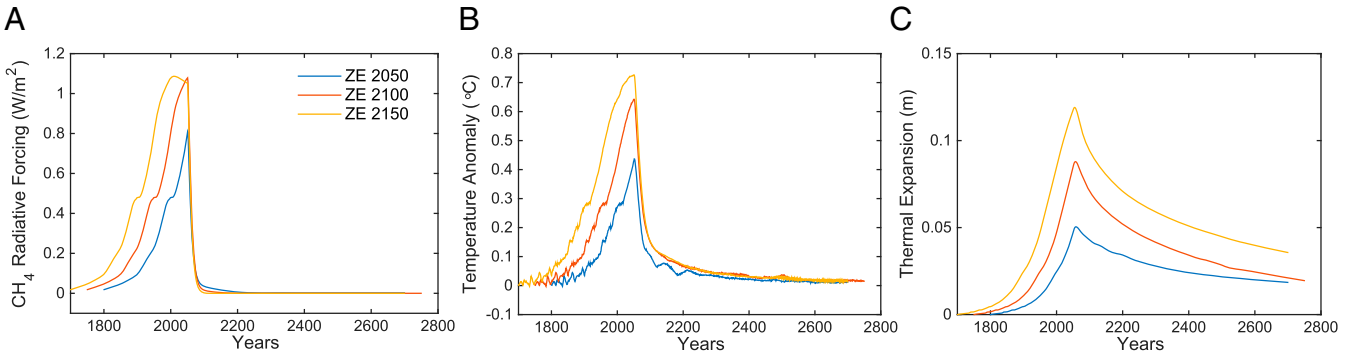

Fig. 3. Climate response computed with the UVic ESCM for scenarios with CH_4 emissions following RCP8.5 to year 2050, 2100, 2150, and zero anthropogenic emissions (ZE) thereafter. Variables are calculated as differences between CO_2 + CH_4 and CO_2-only simulations and are aligned at the time emissions are set to zero (which results in a shift by 50 and 100 y in the ZE2100 and ZE2150 scenarios, respectively). (*A*) CH_4 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:

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

The ratio β/α has units of $W \cdot m^{-2} \cdot K^{-1}$, the same units as the climate-feedback parameter (denoted as λ). The equivalence between the ratio β/α 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 ($d\eta/dt = \gamma N$, where γ 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 λ 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. 4 *A* 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. 4*A*, 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. 4*B*). 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. 4 *C* 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 κ 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 λ, 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

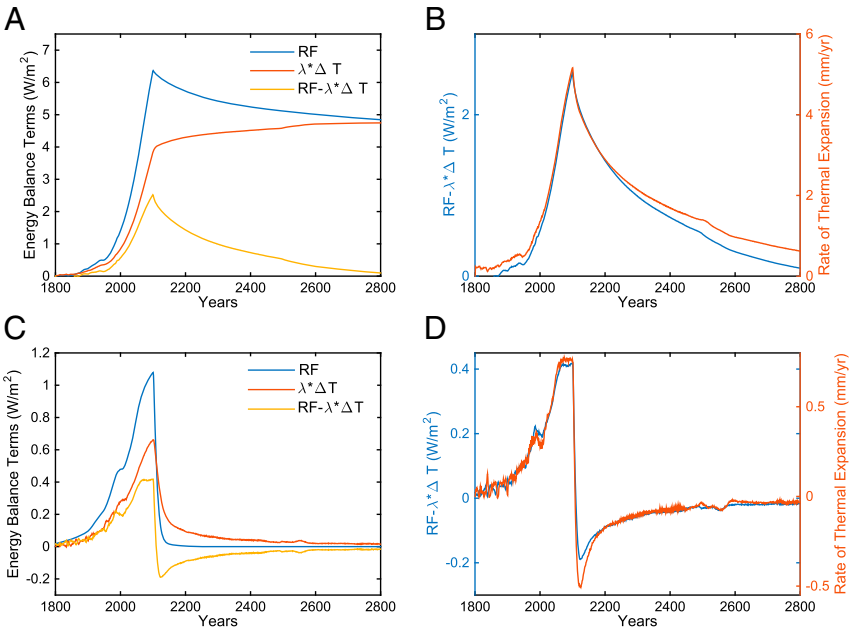

Fig. 4. Energy balance terms and rate of ocean thermal expansion for scenarios with CO_2 (*A* and *B*) and CH_4 (*C* and *D*) emissions following RCP 8.5 to year 2100 and zero anthropogenic emissions thereafter. The simple energy balance model terms are shown by the blue curves in *B* and *D*, which are scaled for comparison with the full model calculation (red curves). The climate response to CH_4 forcing is calculated as the difference between $CO_2 + CH_4$ and CO_2-only simulations. In these calculations, the climate-feedback parameter $\lambda = \beta/\alpha$ is set to 1.0 $W/m^2/K$, the value diagnosed in the standard configuration of the UVic ESCM.

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 ESCM (8, 36), a model of intermediate complexity. This version of the UVic ESCM 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 ESCM. 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.

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