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Optimal temperature overshoot profile found by limiting global sea level rise as a lower-cost climate target

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The global temperature targets of limiting surface warming to below 2.0°C or even to 1.5°C have been widely accepted through the Paris Agreement. However, limiting surface warming has previously been proven insufficient to control sea level rise (SLR). Here, we explore a sea level target that is closer to coastal planning and associated adaptation measures than a temperature target. We find that a sea level target provides an optimal temperature overshoot profile through a physical constraint of SLR. The allowable temperature overshoot leads to lower mitigation costs and more effective long-term sea level stabilization compared to a temperature target leading to the same SLR by 2200. With the same mitigation cost as the temperature target, a SLR target could bring surface warming back to the targeted temperatures within this century, lead to a reduction of surface warming of the next century, and reduce and slow down SLR in the centuries thereafter.

INTRODUCTION

Global sea level rise (SLR) is one of the major severe consequences associated with global warming. Even if surface warming could be kept below 2.0° or 1.5°C by 2100, global SLR will occur for several centuries or even millennia (*1*–*5*). One possible interpretation of a successful climate policy for the next few decades could be that it should avoid global warming–induced impacts on climate, ecosystems, and human societies not only within this century but also for the next centuries and beyond. Here, we perform a proof-of-concept study to introduce a constraint on SLR as a new climate target and compare the economic impact to that of a corresponding temperature target.

SLR behaves qualitatively differently from surface warming in response to atmospheric radiative forcing. SLR is an integrated index of climate response to external radiative forcing. The present and future SLR is mainly driven by thermal expansion of the oceans, by the melt of glaciers and small ice caps, and by the melt of the Greenland and Antarctic ice sheets. The response time scale of each SLR contributor to external forcing is much longer than those of surface warming (*4*, *6*–*8*). SLR due to thermal expansion relates to warming over the full depth of the ocean and thus is mainly determined by the time integral of radiative forcing and hence the time profile of carbon emissions, while surface warming has been related to the upper ocean temperature and thus to the instantaneous radiative forcing and hence the cumulative carbon emissions (*9*). The long-term SLR due to the melt of ice sheets and mountain glaciers is delayed by the thermal inertia and is determined by the time integral of surface warming temporal profile from present to future (*10*).

The contrast between SLR and surface warming in response to anthropogenic carbon emissions is illustrated by the follow thought experiment: We assume two emissions pathways with the same cumulative emissions, one with higher earlier emissions and lower later emissions and the other with lower earlier emissions and higher later emissions. The two emissions pathways would approximately lead to the same surface warming at the end of the emissions. The former emissions pathway would lead to a larger SLR by the end of the emissions but to a smaller SLR rate after the end of the emissions, whereas the latter emissions pathway would lead to a smaller SLR by the end of the emissions but to a larger SLR rate after the end of the emissions. This difference between different emissions pathways arises because later emissions have a smaller effect on the near-term SLR but a larger effect on the future SLR due to its delayed response to radiative forcing. Furthermore, the two assumed emissions pathways could lead to different economic costs of mitigation. This further suggests that a temperature target is not only insufficient to limit long-term SLR but might also be insufficient to minimize the mitigation costs from the point of view of someone who is primarily interested in SLR as global warming impact. Mitigation costs are determined by both the allowable cumulative carbon emissions and the timing of future carbon emissions.

It has been argued that a temperature target alone is insufficient to control transient SLR and many other quantities (*11*). Additional climate targets are called for to fulfil the future sustainable development goals of the United Nations Framework Convention on Climate Change (*11*, *12*). A previous study has proposed various sets of combined climate targets with combined limits to surface warming, SLR, ocean acidification, and loss of primary production on land (*11*). The study estimated allowable cumulative carbon emissions to meet the combined climate targets by applying a probabilistic approach to large-ensemble simulations of an Earth system model of intermediate complexity. However, this previous study did not include an integrated-assessment framework.

In contrast to previous work, we investigate SLR targets with an integrated assessment model. An SLR target would directly connect to impacts of long-term SLR and thus be more directly relevant to coastal planning and adaptation measures related to SLR. To fairly compare the mitigation costs of SLR targets to temperature targets, we present a procedure by which the maximum allowable SLR of an SLR target is deduced from the implied SLR of a temperature target. Thus, we ask what maximum SLR would have been accepted by the

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proponent of the 2.0° and 1.5°C targets within cost-effective decision-making and fix this as the new SLR target. As the time of correspondence, we choose the year 2200, which marks the end of the time horizon considered here, stressing that we focus on long-term SLR. Overall, we have a well-posed method to introduce a numerical analog of a temperature target. A similar numerical analog method has previously been used to investigate targets for atmospheric CO_2 concentration (*13*).

We have substantially augmented the climate physics of the optimizing climate-energy-economy model MIND [Model of Investment and Technological Development; see Materials and Methods and (*14*, *15*)]. The original MIND with cost-effectiveness analysis (CEA) has been developed and used to address the climate mitigation problem. A Ramsey-type module of centennial economic growth (*16*) is coupled to an energy system module. The energy system module resolves energy technologies in terms of fossil fuels, modern renewable energy sources, and traditional nonfossil energy sources. Various energy technologies are represented by individual capital stocks, including learning by doing, and would allow for individual investment paths. The individual investment paths represent MIND's control variables. For this prototypical study, we do not include the controversial technology option of carbon capture and storage. Hence, our model does not allow for negative emissions in optimal mitigation strategies. The macroeconomic and energy system model is coupled to an impulse-response climate model that simulates the global surface temperature response to anthropogenic greenhouse gas emissions (*17*, *18*). We here augment the climate model in MIND from an impulse-response model (*17*) to a three-layer ocean model with much-improved representation of ocean heat uptake (see Materials and Methods). We introduce a global total SLR model with four components, one due to ocean thermal expansion, one due to Greenland ice sheet melting (*3*), one due to Antarctic ice sheet melting (*10*), and one due to mountain glaciers and ice cap melting (*19*) (see Materials and Methods). We do not include the contribution of land water storage in our simple SLR model because the contribution is relatively small compared to the four major contributors (*20*). The newly developed integrated assessment framework has enabled us to investigate a SLR climate target.

MODELING STRATEGY AND RESULTS

Temperature targets versus sea level targets

We characterize scenarios consistent with limiting SLR or SLR rate in the 21st and 22nd centuries below certain levels relative to the preindustrial period, and we describe the differences with respect to scenarios that limit surface warming to below 2.0° or 1.5°C, examining climate response parameters (Fig. 1) and carbon emissions and concentration (Fig. 2). To make sea level targets and temperature targets comparable, we use the year 2200 SLR and the maximum SLR rate resulting from a temperature target as SLR targets (Table 1). Defining climate targets for the year 2200 enables us to address the long-term effect on SLR because SLR has long adjustment time scales to respond to external radiative forcing.

The 2.0°C target shows stabilized surface warming of 2.0°C after the year 2070 (Fig. 1A). The anthropogenic carbon emissions for the 2.0°C target peak at 12.8 gigatonnes of carbon (GtC)/year in 2050, drop sharply to about 3.4 GtC/year by 2070, and stay at about 3.4 GtC/year until 2200 (Fig. 2A). The atmospheric CO_2 concentration for the 2.0°C target peaks at 519 ppmv (parts per million by volume) in 2060 and decreases to 450 ppmv owing to the decreased anthropogenic carbon emissions and a continuous carbon uptake by the climate system (Fig. 2C). Results from the 1.5°C target are similar to the 2.0°C target except for a rescaling of numbers (Figs. 1D and 2, D and F). A small amount of carbon emissions are still permissible, while the surface warming is halting at 2.0° or 1.5°C (Fig. 2, A and D) because the additional radiative forcing due to the small amount of carbon emissions is compensated by ocean heat uptake without warming the surface. Nevertheless, the temperature targets cannot stop the SLR for centuries due to a continued oceanic heat uptake and delayed response to surface warming (Fig. 1, B and E). They can, however, decrease the SLR rate (Fig. 1, C and F).

Table 1. Definition of climate targets. Bold, target variable; normal font, free variable.

Targets	*T* maximum	SLR maximum	SLR rate maximum
T ≤ 2.0°C	**2.0°C**	0.89 m	5.1 mm/year
SLR ≤ 0.89 m	2.3°C	**0.89 m**	5.6 mm/year
SLR ≤ 5.1 mm/year	2.7°C	1.02 m	**5.1 mm/year**
T ≤ 1.5°C	**1.5°C**	0.75 m	4.2 mm/year
SLR ≤ 0.75 m	1.8°C	**0.75 m**	4.6 mm/year
SLR ≤ 4.2 mm/year	2.1°C	0.89 m	**4.2 mm/year**

The SLR targets (SLR, ≤0.89 and ≤0.75 m) allow surface warming overshoot and more anthropogenic carbon emissions compared to the corresponding temperature targets (T ≤ 2.0°C and T ≤ 1.5°C, respectively) within the 21st century (Figs. 1, A and C, and 2, A and C), but by the end of the 22nd century, surface warming drops to 1.76°C for the target SLR of ≤0.89 m and 1.30°C for the target SLR of ≤0.75m (Fig. 1, A and C). Limiting end-of-22nd-century SLR to a particular value cannot stop the long-term SLR due to the slow adjustment in the deep ocean and the delayed response in glaciers and ice sheets. However, the SLR targets slow down the SLR rate after 2200 by about 18% compared to the SLR rate of the corresponding temperature targets (Fig. 1, C and D).

The SLR target is defined as a reinterpretation of a temperature target; hence, both of the climate targets have the same SLR by the year 2200. Coincidentally, SLR targets also imply nearly the same cumulative carbon emissions by year 2200 as the corresponding temperature targets; however, the SLR targets allow more emissions in the short term but require zero emissions in the long term (Fig. 2). The SLR rate targets (SLR rate, ≤5.1 and ≤4.2 mm/year) can slow down surface warming but have no upper limit for long-term surface warming and SLR (Fig. 1). Hence, the SLR rate targets require less reduction of anthropogenic carbon emissions.

Mitigation costs

The different emissions pathways of the SLR and temperature targets imply different climate policies and mitigation costs. We here focus on comparing mitigation costs under SLR and temperature targets.

A common metric of mitigation costs is the relative consumption loss with respect to the business as usual (BAU) scenario. A relative consumption loss provides a time series of losses and therefore gives insight into which target invokes the highest losses (Fig. 3, A and B). The relative consumption loss of the 2.0°C target peaks at 1.7% in 2060 and then declines to almost zero until 2100 (Fig. 3A). The

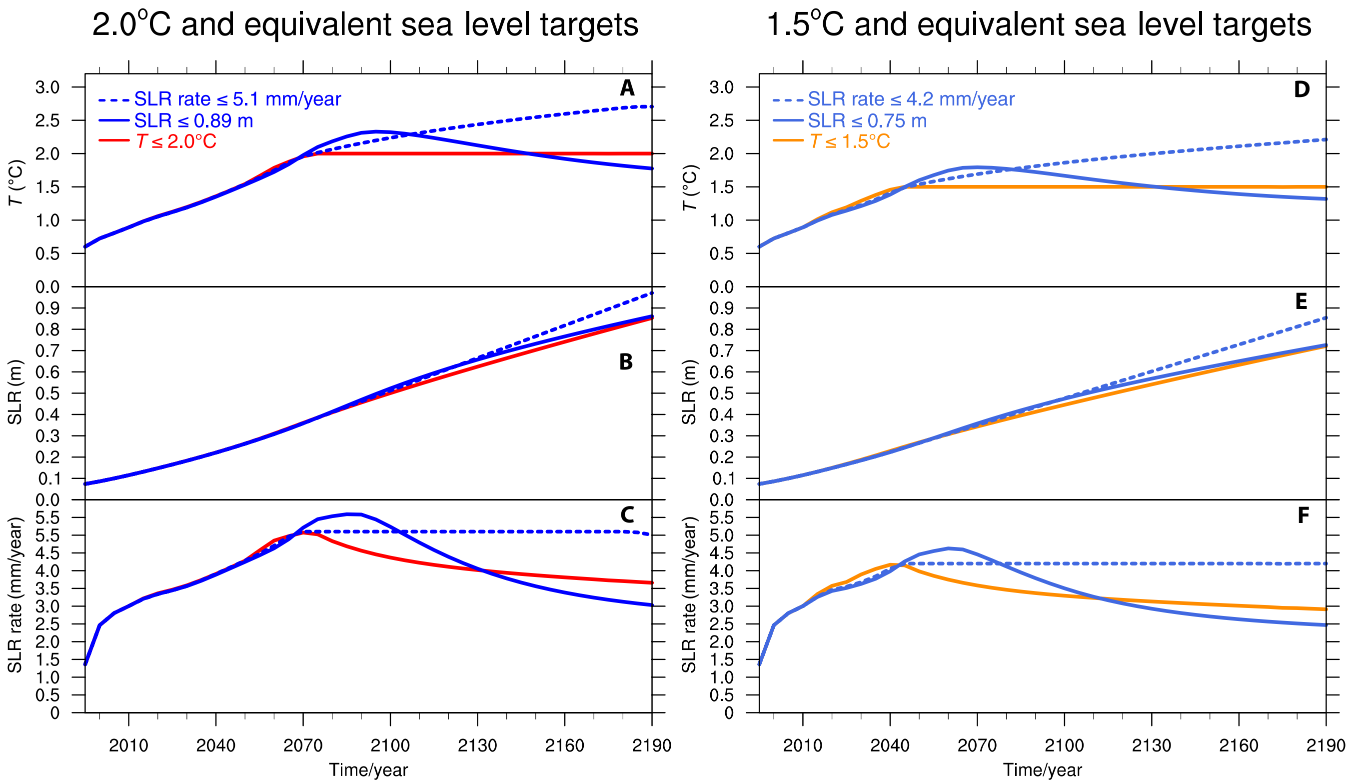

Fig. 1. Climate responses for all climate targets. (**A**) Surface temperature change, (**B**) global SLR, and (**C**) global SLR rate for the 2.0°C target and all corresponding sea level targets. (**D**) Surface temperature change, (**E**) global SLR, and (**F**) global SLR rate for the 1.5°C target and all corresponding sea level targets.

higher SLR target (SLR, ≤0.89 m) and SLR rate target (SLR rate, ≤5.1 mm/year) lead to lower maximum relative consumption losses by about 23% (Fig. 3A) and also lead to a later appearance of the peak compared to the 2.0°C target. The lower SLR target (SLR, ≤0.75 m) and SLR rate target (SLR rate, ≤4.2 mm/year) also show lower and later maximum relative consumption losses compared to the 1.5°C target (Fig. 3B).

We also use certainty and balanced growth equivalents (CBGEs) (*21*, *22*) to assess welfare loss as the mitigation costs for different climate targets. CBGE gives the change in initial consumption that is necessary to reach the same difference in welfare when mapping the policy and baseline consumption paths onto two stylized consumption paths of constant, identical growth rates and represent one established way of time-aggregating consumption paths. We use CBGE because they allow expressing relative, time-aggregated consumption losses in the most consistent manner. The difference in CBGE between the selected climate target and the BAU expresses the difference between two scenarios as a constant change in relative consumption (*22*). While projecting economic numbers for the next century might seem questionable, we note that for any of the scenarios considered, time-aggregated mitigation costs are mainly driven by the more robust consumption losses of the current century (Fig. 3). The CBGE loss of the 2.0°C target is 0.27%, and the CBGE loss of the 1.5°C target is about 1.0%, suggesting that the change from the 2.0°C target to the 1.5°C target substantially increases the mitigation costs (Fig. 3C). However, the CBGE losses of the SLR targets are only half of the CBGE loss of the corresponding temperature targets (Fig. 3C). We conclude that the mitigation cost of an SLR target is lower than that of the temperature target with similar SLR by 2200.

Our economic model is based on the simplifying assumption of maximum flexibility in the energy sector. The hard-to-decarbonize transport sector is not explicitly distinguished from the electricity sector. Hence, our model would deliver lower bounds on mitigation costs (in terms of consumption losses), and in turn, we expect the economic effects reported in our study to become even stronger when repeated by a high-resolution energy system model. We implicitly use a certain equilibrium climate sensitivity value of 3.2 K, inferred from one particular Earth system model [the low-resolution version of the Max Planck Institute Earth System Model (MPI-ESM) (*23*)]; hence, a direct comparison with 66% target compliance–oriented values from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) of Working Group III (*24*) is difficult. A detailed description of the three modules of MIND can be found in (*14*).

Sensitivity to choice of sea level target

We repeat our model runs with limiting SLR at different levels over the range of 0.64 to 0.94 m in steps of 0.01 m. The lower bound of SLR of 0.64 m by 2200 is the lowest SLR target, for which our model is able to find feasible emissions reduction pathways. This lowest SLR target of SLR is ≤0.64 m, which requires an immediate reduction of carbon emissions and zero carbon emissions by 2040 (Fig. 4) and leads to a maximum surface warming of 1.41°C within the 21st century, a surface warming of 1.19°C by 2100, and a surface warming of 1.01°C by 2200 (Figs. 4A and 5).

The SLR target of SLR of ≤0.69 m incurs the same mitigation costs as the 1.5°C target and allows a maximum temperature overshoot of 0.08°C (to 1.58°C) within the 21st century. Surface warming reaches 1.40°C by 2100 and 1.14°C by 2200 (Fig. 5, A and B). This SLR target

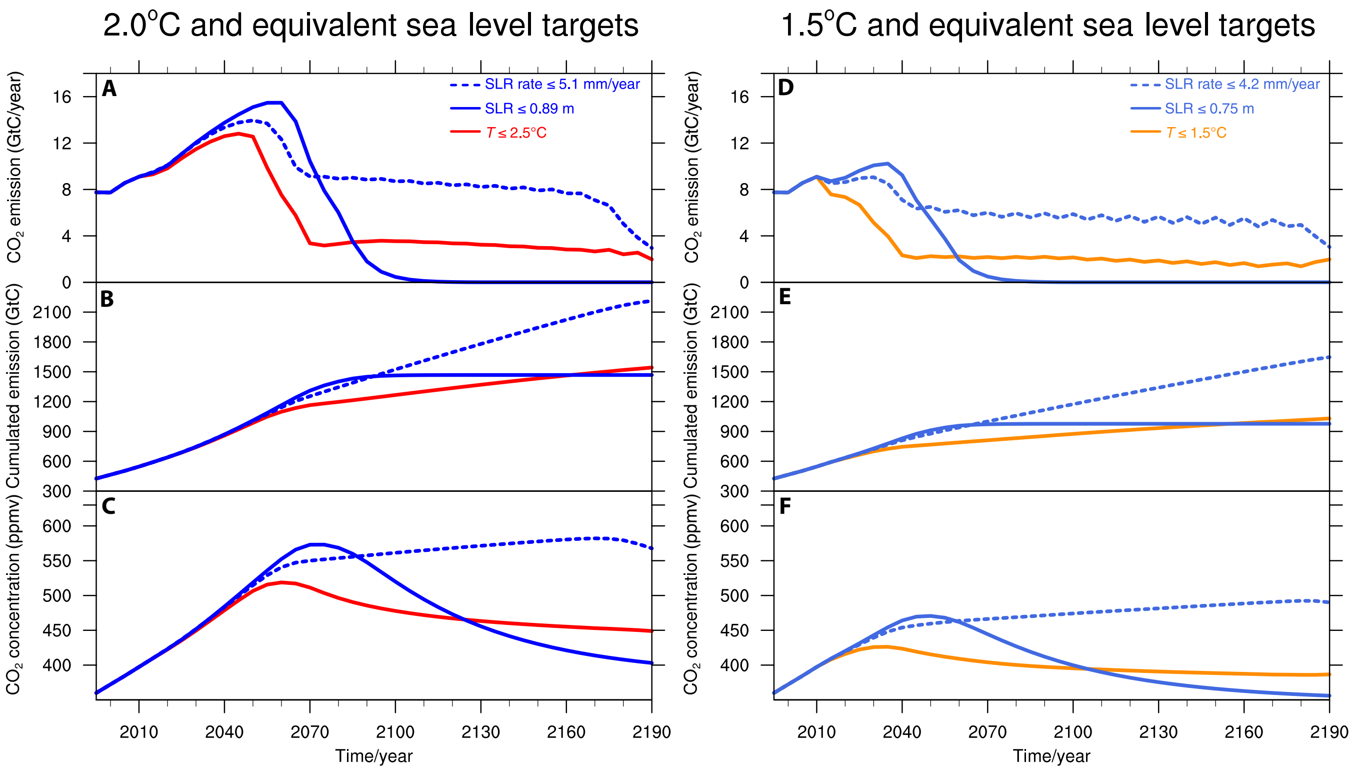

Fig. 2. Carbon emissions and concentrations for all climate targets. (**A**) Carbon emissions, (**B**) cumulative carbon emissions, and (**C**) atmospheric CO_2 concentration for the 2.0°C target and all corresponding sea level targets. (**D**) Carbon emissions, (**E**) cumulative carbon emissions, and (**F**) atmospheric CO_2 concentration for the 1.5°C target and all corresponding sea level targets.

requires an immediate reduction of anthropogenic carbon emissions and zero emissions by 2070 (Fig. 4B). The SLR target of SLR of ≤0.82 m incurs the same mitigation costs as the 2.0°C target and allows a maximum temperature overshoot of 0.06°C (to 2.06°C) within the 21st century. Surface warming reaches 2.0°C by 2100 and 1.52°C by 2200 (Fig. 5, A and B). This SLR target allows anthropogenic carbon emissions to peak at 12.9 GtC/year in 2045 and requires a reduction from the peak to zero within 40 years by 2095 (Fig. 4). The SLR targets of SLR of ≤0.69 and ≤0.82 m by 2200 reduce surface warming by about 24%, decrease the total SLR by about 8%, and reduce the SLR rate by about 30% within the 22nd century, compared to the respective temperature targets of equal cost (Fig. 5, B to D).

With the same mitigation costs as the corresponding temperature target, the SLR target limits surface warming in compliance with the original temperature target to an accuracy better than 0.1°C in the short term, brings surface warming below the targeted temperature, and reduces SLR in the long term (Fig. 4A). Overall, SLR targets are sufficient to limit climate change in both short and long terms and are also sufficient to suggest a mitigation strategy with a minimized mitigation cost.

DISCUSSION

Possibility of rapid SLR due to nonlinear threshold behavior in ice sheets

The simple climate and SLR models used here are reliable enough to reproduce the climate response to atmospheric CO_2 forcing of the state-of-the-art climate model projections assessed in the IPCC AR5 (fig. S1). However, the simple SLR model does not include nonlinear components with strong threshold behavior of ice sheet melt, which might strongly influence future SLR (*3*, *25*–*29*). Using a comprehensive model coupling ice sheet and climate dynamics, a recent study (*29*) has shown that the Antarctic ice sheet can rapidly collapse and has the potential to substantially increase SLR due to marine ice cliff instability (MICI) in the next centuries under the medium and high emissions scenarios of representative carbon pathway 4.5 (RCP4.5) and RCP8.5. However, a new study (*30*) has revisited the MICI study (*29*) and questioned whether there is sufficient evidence to support MICI playing a role in SLR. Although the contribution of Antarctic MICI is still under debate under high emissions scenarios, both of the two studies agree that a rapid loss of the Antarctic ice sheet due to MICI is exceptionally unlikely in the low emissions scenarios of RCP2.6.

The Greenland ice sheet is expected to completely disappear due to global warming of more than 2.0°C (*20*). This complete melt, however, is a very slow process, lasting several millennia (*20*). Some of our SLR targets show temporary overshoot of surface warming above 2.0°C only for several decades, and thereafter, surface warming drops below 2.0°C by 2200 in all present SLR targets. Overall, we conclude that under relative low emissions scenarios, our simple climate and SLR models serve the task of climate target development in our study.

Implications for the Paris Agreement

In the 21st yearly session of the Conference of the Parties in Paris in 2015, SLR threats to the Small Island Developing States (SIDS)

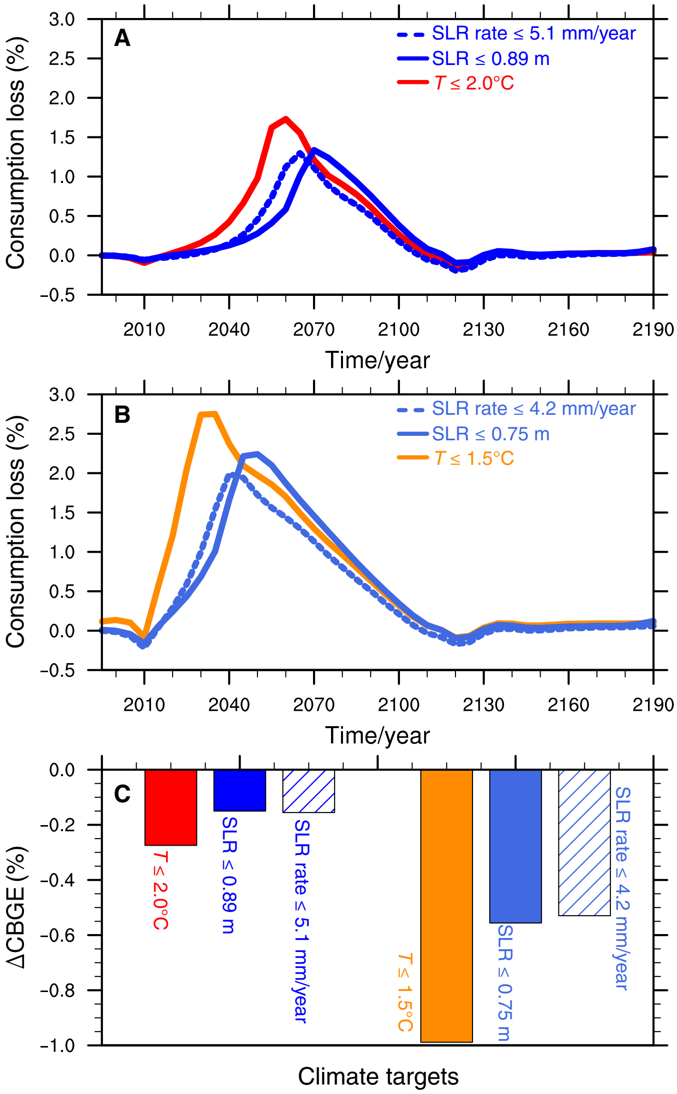

Fig. 3. Mitigation costs for all climate targets. Consumption loss for (**A**) the 2.0°C target and all corresponding sea level targets and (**B**) the 1.5°C target and all corresponding sea level targets. (**C**) CBGE loss for all climate targets. CBGE gives the change in initial consumption that is necessary to reach the difference in welfare assuming equal consumption growth in both the defined climate target and the BAU scenario (*21*, *22*).

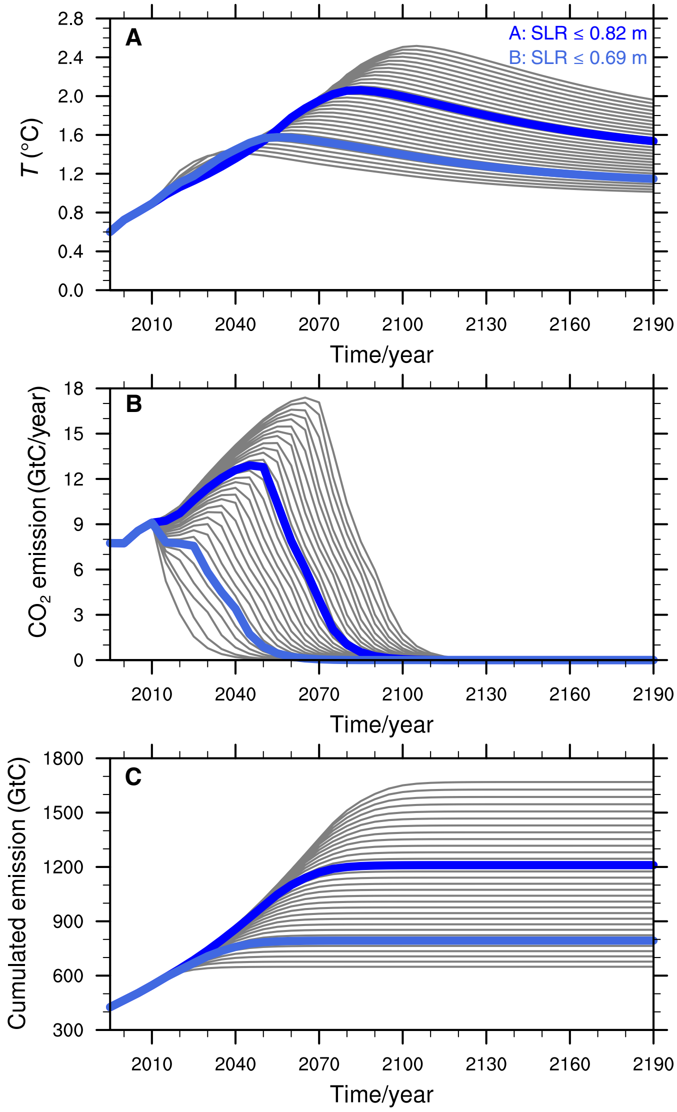

Fig. 4. Surface temperature change, carbon emissions, and cumulative carbon emissions for different SLR targets. (**A**) Surface temperature change for limiting global SLR at different levels from 0.64 to 0.94 m until 2200. (**B**) Carbon emissions for limiting global SLR at different levels from 0.64 to 0.94 m until 2200. (**C**) Cumulative carbon emissions for limiting global SLR at different levels from 0.64 to 0.94 m until 2200.

prompted a commitment to strive for a lower global temperature target goal of limiting surface warming below 1.5°C. However, an SLR target more directly relates to their existential threats. Here, we have established the first integrated assessment framework of global SLR targets related to the temperature targets of the Paris Agreement and investigated a more sustainable solution to limit global SLR. Because SLR is determined by the time integral of external forcing, the time profiles of the anthoropogenic emissions and the surface warming matter for future long-term SLR. Hence, it is vital to explore a time profile–optimized mitigation strategy associated with a target of limiting future long-term SLR. Even if surface warming were limited below 1.5° or 2.0°C by 2100, SLR would continue for centuries, and as a compromise between targeting long-term SLR and applicability of our integrated-assessment framework, we choose 2200 as the reference year for an SLR target. An SLR target, whose execution is optimally profiled in time, may well be more efficient economically for the same cumulated emissions than a temperature target that achieves the same SLR by year 2200.

Our results emphasize a key effect of carbon emissions pathways on the future SLR after the 21st century. The shape of carbon emissions pathways will strongly influence future SLR after the 21st century and generally affect SIDS over centuries. To reduce SLR-induced impacts on SIDS, a target is required that not only keeps surface warming below a certain level but also reduces surface warming substantially thereafter. We find that a global SLR target will provide a more sustainable and a lower-cost solution to limit both short-term and long-term climate changes for stakeholders who primarily care about SLR among all global warming impact categories compared to a temperature target with the same SLR by 2200. In addition, proponents of the original temperature target might

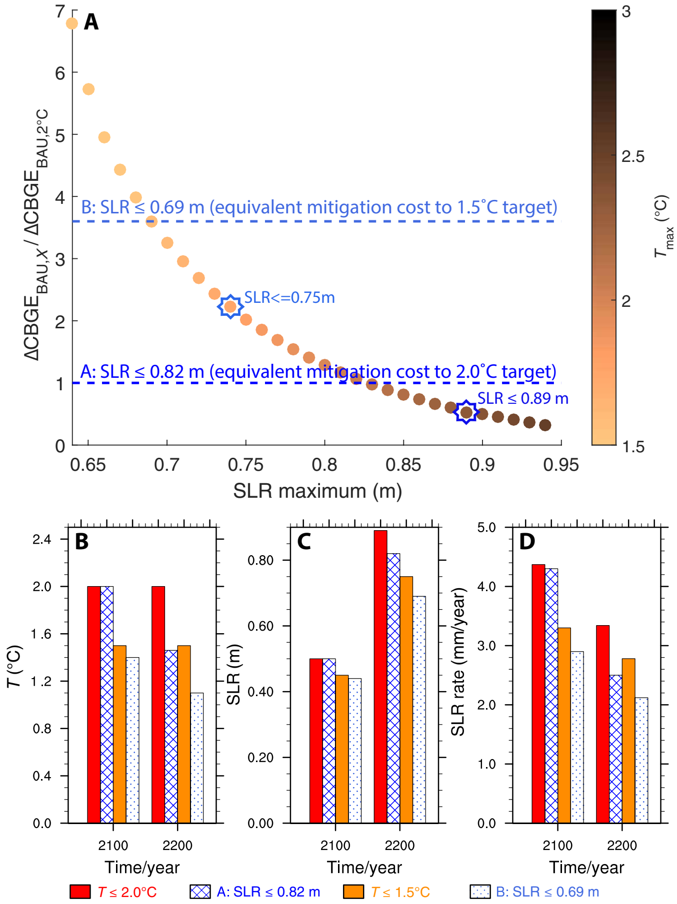

Fig. 5. Characteristics of different SLR targets. (**A**) Normalized CBGE loss and surface temperature change maximum for limiting global SLR at different levels from 0.64 m to 0.94 m until 2200. (**B**) Surface temperature change, (**C**) global SLR, and (**D**) global SLR rate at years 2100 and 2200 for temperature targets and SLR targets of equivalent mitigation costs.

also find our scenario acceptable, as the temperature overshoot is below 0.1°C.

We find that the SLR target can provide a temperature overshoot profile through a physical constraint rather than arbitrarily defining an overshoot range of temperature as acceptable. Temperature targets with a limited overshoot have been invoked to make the 2.0° and 1.5°C targets feasible in the context of real-world United Nations climate policy; however, rational constraints on the temperature overshoot have been unclear (*31*–*33*). SLR targets can be viewed as a reinterpretation of the 2.0° and 1.5°C targets and can provide a rational justification of a certain temperature overshoot for stakeholders who primarily care about SLR. Our present framework with reinterpretation of the widely agreed temperature targets can, in principle, be transferred from SLR targets to impact-related climate targets and can be used to identify a more sustainable path toward meeting the Paris Agreement.

MATERIALS AND METHODS

Climate targets and CEA in MIND

CEA was used to find the minimum mitigation costs, which are calculated as the impact of investments in different mitigation options on the overall macroeconomic costs of climate protection measured in terms of welfare losses for meeting a selected climate target as expressed as

$$\max_I W = \max_I \sum_{t=0}^{t_{\mathrm{end}}} \underbrace{U[C(I(t),t)]}_{\text{Utilityfunction}} P(t)\, e^{-\delta t} \text{ with } \underbrace{\forall_t\, T(I(t),t) \le T_{\max}}_{\text{target}} \tag{1}$$

Welfare W is the time integral of discounted utility function $U(C)$, $C(I)$ is the per capita consumption, $I(t)$ is the investment to energy technologies, $P(t)$ is the exogenous population, t is time, δ is the pure rate of time preference (1% per year), and $e^{-\delta t}$ is the time-varying discount factor. $T(I(t), t)$ is the time series of the target variable and $T_{\max}$ is the given target. We defined three climate targets, for surface temperature, SLR, and SLR rate. CEA does not require a climate damage function but instead calculates the mitigation costs of different climate targets.

The optimization period of MIND is from 1995 to 2200, with a time step of 5 years. The optimization period cannot go beyond 2200 because fossil-fuel energy will be replaced by renewable energy until 2200 in the BAU scenario without any environmental constraint, owing to the lower price of renewable energy technologies in the long term (*14*). Results shown here are only until 2190 because the capital stock will only be consumed and no investment will take place at the end of the simulation.

A three-layer ocean model and parameter calibration

The three-layer ocean model simulates ocean temperature change in mixed layer, thermocline, and deep ocean

$$\frac{dT_{\mathrm{ML}}}{dt} = \frac{R}{C_{\mathrm{ML}}} - \frac{\alpha\, T_{\mathrm{surf}}}{C_{\mathrm{ML}}} - \frac{w_{\mathrm{E}}}{D_{\mathrm{ML}}}(T_{\mathrm{ML}} - T_{\mathrm{TC}}) \tag{2}$$

$$\frac{dT_{\mathrm{TC}}}{dt} = \frac{w_{\mathrm{E}}}{D_{\mathrm{TC}}}(T_{\mathrm{ML}} - T_{\mathrm{TC}}) - \frac{w_{\mathrm{D}}}{D_{\mathrm{TC}}}(T_{\mathrm{TC}} - T_{\mathrm{D}}) \tag{3}$$

$$\frac{dT_{\mathrm{D}}}{dt} = \frac{w_{\mathrm{D}}}{D_{\mathrm{D}}}(T_{\mathrm{TC}} - T_{\mathrm{D}}) \tag{4}$$

$$T_{\mathrm{surf}} = \beta \cdot T_{\mathrm{ML}} \tag{5}$$

$$R = 0.5 \cdot R_{4\times\mathrm{CO_2}} \cdot \ln(c/278.)/\ln(2) + R_{\mathrm{SO_2}} + R_{\mathrm{OGHG}} \tag{6}$$

$$\frac{dF}{dt} = E \tag{7}$$

$$\frac{dc}{dt} = \epsilon E + \mathrm{B}F - \delta c \tag{8}$$

where ocean temperature change (T_{ML}, T_{TC}, and T_{D}) is the deviation from a preindustrial steady climate, R is radiative forcing from anthropogenic emissions, α is the climate feedback parameter, w_{E} is Ekman pumping velocity, C_{ML} is mixed-layer heat capacity, D_{ML} is mixed-layer depth, D_{TC} is thermocline depth, D_{D} is deep ocean depth, w_{D} is deep ocean vertical velocity, c is atmospheric CO_2 concentration in units of ppm, $R_{4\times\mathrm{CO2}}$ is radiative forcing of atmospheric CO_2 quadrupling, R_{SO2} is radiative forcing from SO_2, a side combustion product in coal power plants, R_{OGHG} is radiative forcing from other greenhouse gases, F is cumulative anthropogenic CO_2 emissions, E is anthropogenic CO_2 emissions, $\epsilon = 0.47$ ppmv/GtC

(CO_2 emissions to concentration conversion factor), $\delta = 0.0215\ \mathrm{a}^{-1}$ is the carbon uptake response parameter, and $B/(\epsilon\delta) = 0.15$ is the atmospheric retention factor. We introduced a scaling factor (β) to express global surface warming (T_{surf}) with ocean mixed-layer temperature because the land surface warms faster and stronger than the ocean surface in a future warm climate.

Before we introduced this simple climate model to MIND, we derived the key parameters of radiative forcing ($R_{4\times CO2}$), climate feedback parameter (α), surface warming scaling factor (β), Ekman pumping velocity (w_{E}), and deep ocean vertical velocity (w_{D}) from a 300-year simulation with an abrupt $4\times CO_2$ simulation of the lower-resolution version of Max Planck Institute for Meteorology Earth System Model (MPI-ESM-LR) (*23*). We estimated $R_{4\times CO2}$ and α with a linear regression between surface warming and heat flux imbalance at the top of atmosphere according to (*34*) and used a nonlinear least-squares curve-fitting method to gain an optimized w_{E} and w_{D}, where the three-layer ocean mode can reproduce the ocean warming as shown in MPI-ESM-LR (fig. S1). All parameters are given in table S1.

Global SLR model

We calculated global SLR (η'_{total}) as the sum of thermosteric SLR (η'_{S}), of Greenland ice sheet melt (η'_{GrIS}), of Antarctic ice sheet melt (η'_{AntIS}), and of mountain glaciers and ice cap melting (η'_{MG})

$$\eta'_{\mathrm{total}} = \eta'_{\mathrm{S}} + \eta'_{\mathrm{GrIS}} + \eta'_{\mathrm{AntIS}} + \eta'_{\mathrm{MG}} \qquad (9)$$

Here, (η'_{S}) is directly estimated from ocean temperature change using constant thermal and haline expansion coefficients

$$\eta'_{\mathrm{S}} = \gamma_{\mathrm{ML}} \cdot T_{\mathrm{ML}} \cdot D_{\mathrm{ML}} + \gamma_{\mathrm{TC}} \cdot T_{\mathrm{TC}} \cdot D_{\mathrm{TC}} + \gamma_{\mathrm{D}} \cdot T_{\mathrm{D}} \cdot D_{\mathrm{D}} \qquad (10)$$

where γ_{ML}, γ_{TC}, and γ_{D} are thermal expansion coefficients. We optimized the thermosteric SLR model with an abrupt $4 \times CO_2$ simulation of MPI-ESM-LR using a nonlinear least-squares curve-fitting method to obtain thermal expansion coefficient (γ_{ML}, γ_{TC}, and γ_{D}). The sea level model reproduces the evolution of thermosteric SLR as shown in MPI-ESM-LR (fig. S2). All constant key parameters used in the three-layer ocean model and sea level model are described in table S1.

(η'_{GrIS}) is calculated with the empirical model from (*3*, *35*)

$$\eta'_{\mathrm{GrIS}} = \sum_{\mathrm{year}=1850} (71.5\cdot T_{\mathrm{surf}} + 20.4\cdot T^2_{\mathrm{surf}} + 2.8\cdot T^3_{\mathrm{surf}})/3.61 \times 10^5 \qquad (11)$$

(η'_{AntIS}) is calculated with two linear terms of (*10*). The two linear terms contain a term linear in time to account for rapid dynamical changes in the ice sheet and a term linear in cumulative surface warming to account for surface mass balance changes

$$\eta'_{\mathrm{AntIS}} = \sum_{\mathrm{year}=1995} (0.00074 + 0.00022\cdot T_{\mathrm{surf}}) \qquad (12)$$

(η'_{MG}) is calculated with the empirical model from (*19*, *36*)

$$\eta'_{\mathrm{MG}} = \sum_{\mathrm{year}=1850} 0.0008\cdot T_{\mathrm{surf}} \cdot (1-\eta'_{\mathrm{MG}}/0.41)^{1.646} \qquad (13)$$

Simulated present climate and projected future climate

We took the total effective radiative forcing of the historical period and future scenarios of RCPs from Annex II of the IPCC AR5 (fig. S1A) (*35*). Our simple climate model largely reproduces the observed surface warming and SLR in the historical period, and the projected surface warming, SLR, and SLR rate under different RCPs by 2100 lie within the range of the comprehensive projection of IPCC AR5 (fig. S1, B to D). Hence, our simple climate model can reasonably simulate the climate response to anthropogenic carbon emissions and serve the task of climate target development in the integrated assessment framework.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/2/eaaw9490/DC1

Note S1. This auxiliary material contains three supplementary figures and one supplementary table, which are referred to in the main manuscript

Fig. S1. Historical evolution and future projections as simulated with our three-layer ocean model.

Fig. S2. Simulated ocean-temperature change with an instantaneous quadrupling of atmospheric CO_2 (relative to preindustrial conditions) and then held fixed over 300 years.

Fig. S3. Simulated global thermosteric SLR with an instantaneous quadrupling of atmospheric CO_2 (relative to preindustrial conditions) and then held fixed over 300 years.

Table S1. Default parameters for the three-layer ocean model.

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Acknowledgments: We thank H. Li and P. Landschützer from the Max Planck Institute for Meteorology and O. Geden from the German Institute for International and Security Affairs for thoughtful comments on this manuscript and O. Edenhofer from the Potsdam Institute for Climate Impact Research (PIK) for providing the source code of MIND. We also thank L. Kornblueh for producing the long simulation of atmospheric CO_2 quadrupling and to the Deutsches Klimarechenzentrum (DKRZ) facilities. **Funding:** C.L. and S.H. were supported through the Clusters of Excellence "CliSAP" (EXC177) and "CLICCS" (EXC2037), University Hamburg, funded through the German Research Foundation (DFG). J.M. was supported by the Max Planck Society for the Advancement of Science. **Author contributions:** C.L., H.H., and J.M. conceived the original idea for this study. C.L. carried out the simulations with the help of S.H. and performed the analyses. C.L. wrote the manuscript with inputs from J.M. and H.H. C.L., H.H., S.H., and J.M. discussed the results and contributed to improvements of the manuscript. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** The authors declare that the data supporting the findings of this study and all computer scripts to conduct the results and reproduce figures of this study are archived by the Max Plank Institute for Meteorology and can be obtained by contacting the corresponding author or publications@mpimet.mpg.de.

Submitted 8 February 2019
Accepted 11 November 2019
Published 8 January 2020
10.1126/sciadv.aaw9490

Citation: C. Li, H. Held, S. Hokamp, J. Marotzke, Optimal temperature overshoot profile found by limiting global sea level rise as a lower-cost climate target. *Sci. Adv.* **6**, eaaw9490 (2020).

Science Advances

Optimal temperature overshoot profile found by limiting global sea level rise as a lower-cost climate target

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Sci Adv **6** (2), eaaw9490.
DOI: 10.1126/sciadv.aaw9490

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