Environmental Research Letters

LETTER

Effect on the Earth system of realizing a 1.5 °C warming climate target after overshooting to the 2 °C level

Koaru Tachiiri1, Diego Silva Herran2, Xuanming Su1 and Michio Kawamiya1
1 Japan Agency for Marine-Earth Science and Technology, 3173-25 Showamachi, Kanazawa-ku, Yokohama 236-0001, Japan
2 Institute for Global Environmental Strategies, 2108-11 Kamiyamaguchi, Hayama, Kanagawa 240-0115, Japan
E-mail: tachiiri@jamstec.go.jp
Keywords: Earth system model, integrated assessment model, 1.5 °C target, 2 °C target, stabilization, overshoot
Supplementary material for this article is available online

Abstract
An Earth system model (ESM) was used to investigate the effect of reaching the target of 1.5 °C warming (relative to preindustrial levels) after overshooting to the 2 °C level with respect to selected global environment indicators. Two scenarios were compared that diverged after reaching the 2 °C level: one stayed at the 2 °C level, and the other cooled to the 1.5 °C level. Unlike the internationally coordinated model intercomparison projects, the scenarios were developed for a specific climatic model with emissions and land use scenarios consistent with socioeconomic projections from an integrated assessment model. The ESM output resulted in delayed realization of the 1.5 °C and 2 °C targets expected for 2100. The cumulative CO2 emissions for 2010−2100 (2300) were 358 (−53) GtCO2 in the 2 °C scenario and −337 (−936) GtCO2 in the 1.5 °C scenario. We examined the effect of overshooting on commonly used indicators related to surface air temperature, sea surface temperature and total ocean heat uptake. Global vegetation productivity at 2100 showed around a 5% increase in the 2 °C scenario without overshooting compared with the 1.5 °C scenario with overshooting, considered to be caused by more precipitation and stronger CO2 fertilization. A considerable difference was found between the two scenarios in terms of Arctic sea ice, whereas both scenarios indicated few corals would survive past the 21st century. The difference in steric sea level rise, reflecting total cumulative ocean heat uptake, between the two scenarios was <2 cm in 2100, and around 9 cm in 2300 in the Pacific Island region. A large overshoot may reduce the eventual difference between targets (i.e. 1.5 °C in contrast to 2 °C), particularly in terms of the indicators related to total ocean heat uptake, and to sensitive biological thresholds.

1. Introduction
Recent negotiations between the parties of the United Nations Framework Convention on Climate Change have highlighted the need to restrict the warming of global mean temperatures to below 2 °C (relative to preindustrial levels) during the 21st century and beyond. Moreover, it has been acknowledged that efforts should be pursued to restrict global warming to 1.5 °C to avoid dangerous climate change induced by anthropogenic greenhouse gases (GHGs). These negotiations led to the publication of the Special Report on the impacts of global warming of 1.5 °C (hereafter, SR1.5; IPCC 2018).

Certain aspects of the Earth system’s response are sensitive to differences between the 1.5 °C and 2 °C targets. For example, Schellnhuber et al (2016) showed that the West Antarctic and Greenland ice sheets, Arctic summer sea ice, Alpine glaciers and coral reefs might have ‘tipping points’ between 1.5 °C and 2 °C warming. Gattuso et al (2015) compared the risks to key organisms associated with warming. It was found that warm-water corals were highly sensitive to changes in sea surface temperature (SST) and that even the current SST represents some risk.

Among the various risks to specific natural, managed and human systems, SR1.5 focused on warm-water corals, mangroves, small-scale fisheries, the
Arctic region, terrestrial ecosystems, coastal flooding, fluvial flooding, crop yields, tourism, and heat-related morbidity and mortality. The report concluded that substantial global differences in these aspects are expected between the 1.5 °C and 2 °C global mean surface temperature (GMST) anomalies. Coral reefs were identified as the indicator most sensitive to warming.

Assessment of the impacts of ambitious climate targets requires emission scenarios consistent with realistic socioeconomic scenarios. Heuristic model intercomparison assessments, including some overshoot scenarios, require experiments with both emission and land use scenarios that are developed by ‘harmonizing’ multimodel outputs from socioeconomic (or integrated assessment) models. Such model intercomparison assessments are planned, including scenarios consistent with the realization of the 1.5 °C and 2 °C targets (O’Neil et al 2016). However, given the urgency of the issue, some studies have used simplified approaches without integrated assessment models (IAMs) (Shiogama 2017). For example, Sanderson et al (2016, 2017) used a simplified scenario without an IAM, and Schleussner et al (2016) used outputs corresponding to a temperature rise of 1.5 °C and 2 °C in an experiment that increased the temperature to 4 °C. Mitchell et al’s (2016) study was also planned as a climate model intercomparison without consideration of socioeconomic scenarios. In these approaches, however, the mitigation costs necessary to achieve the emission/concentration scenario were beyond the scope of analysis.

The difficulty of realizing a stringent target depends on the basic properties of the climate system—climate sensitivity, ocean heat uptake (OHU) and climate-carbon cycle feedbacks. When the transient climate response, determined by climate sensitivity and OHU, is large and/or when the climate-carbon cycle feedback is strong, the carbon budget available to achieve the temperature target decreases. In such a case, overshooting may be unavoidable in realizing the 1.5 °C target, because it is difficult to get feasible socioeconomic pathways (normally obtained by running an IAM) leading to stabilization of the global temperature change at that level. In general, the scenario literature indicates that the probability of keeping temperature increases below this target without overshoot are very low (Rogelj et al 2015). Consequently, GHG emissions would need to reach negative values, which would require massive expansion of CO₂ removal technologies such as bioenergy combined with carbon capture and storage (CCS) in the early decades of the 21st century. These technologies, however, will require robust policies facilitating financial support and minimizing adverse effects (Honegger and Reiner 2018). Other alternatives for drastically reduced emissions include changes in lifestyle, enhancing non-CO₂ emission reductions and accelerating renewable energy deployment (van Vuuren et al 2018). In addition, the role of negative emissions and the ultimate peak in global mean temperatures will depend on population growth, economic growth and technological progress (Rogelj et al 2018).

A concern regarding overshooting from the perspective of the Earth system response is that while some aspects are not history-dependent and are determined only by current conditions, for other aspects, such as ocean heat content, history does matter. In the latter case, the benefit of reaching a stringent target with overshooting might decline, because during the overshoot irreversible effects may occur. Palter et al (2018) concluded that steric sea level rise, Atlantic meridional circulation, Antarctic sea ice coverage, and the spatial pattern of surface air temperatures are impacted by overshooting. Other studies (e.g. Tsutsui et al 2007, Zickfeld et al 2012) support this conclusion for steric sea level rise. This indicates that overshooting could affect at least some variables.

Existing studies on overshoot scenarios are separated into those focusing on the Earth system response using simple (i.e. without socio-economic background) overshooting scenarios (e.g. Tsutsui et al 2007, Zickfeld et al 2012, Mathiesius et al 2015, Tokarska and Zickfeld 2015, Palter et al 2018), and those focusing on socio-economic requirements using IAMs (e.g. den Elzen and van Vuuren 2007, Azar et al 2013, Ricke et al 2017). In contrast, this study conducted an experiment using an Earth system model (ESM) that incorporated scenarios developed using an IAM. The outcomes of key climate impact indicators were evaluated by focusing on the differences between scenarios considering temperature stabilization at 2 °C warming (relative to preindustrial levels) and the attainment of the 1.5 °C target after overshooting to 2 °C.

2. Method

Analysis of the 2 °C stabilization scenario and the 1.5 °C overshooting scenario through 2300 were conducted by first running a climate model using emission scenarios from a socioeconomic model (figure S1 is available online at stacks.iop.org/ERL/14/124063/mmmedia). Then, certain climate indicator outputs from the climate model, considered important in discussing the differences between the 1.5 °C and 2 °C scenarios, were compared.

2.1. Socioeconomic model

The emissions and land use scenarios were developed using the GCAM-SOUSEI model. This model is based on the Global Change Assessment Model (GCAM), which is an IAM that reflects the economy, energy sector, and agricultural and land use sectors under a partial equilibrium approach (Kim et al 2006). Mitigation of GHGs is achieved by a carbon price on global CO₂ emissions from fossil fuels and industry (FFI) from 2020. Mitigation of other Kyoto GHG emissions...
is represented by marginal abatement cost curves, which indicate the rate of emissions reduction achieved for each GHG at a given carbon price. Non-CO₂ GHGs are converted to CO₂ equivalents assuming 100 year global warming potentials. A description of the IAM is presented in the supplementary information (SI). In GCAM-SOUSEI, GHG concentrations, radiative forcing and temperature change are calculated by the Model for the Assessment of greenhouse-gas Induced Climate Change (MAGICC), which is a simple climate model that represents global and hemispheric upwelling-diffusion and energy balances. It includes a range of gas cycles and considers climate-carbon cycle feedbacks as exponential functions of anomalies in GMST (Meinshausen et al 2011).

Similar to Sanderson et al (2017), MAGICC was tuned to the equilibrium climate sensitivity (ECS) of the ESM used (see below) to obtain an outcome of global temperature change consistent with the temperature targets defined in the scenario setting. This represents a clear departure from conventional analysis using IAMs, where emission scenarios developed for climate targets are modeled assuming central values for all parameters. For this purpose, we evaluated the climate outcomes of the IAM for the Representative Concentration Pathway (RCP) 4.5 (Thomson et al 2011) and RCP2.6 (van Vuuren et al 2011) scenarios, changing the value of the ECS to match the climate outcomes from the above scenarios performed with the ESM (Hajima et al 2012). In this study, a scenario with stabilization at 1.5 °C without overshooting was not feasible with the ECS tuned to the ESM.

2.2. Scenario developed by the IAM and put into the ESM
The development of the two scenarios in this study are described in detail in SI. The first scenario considers stabilization of global temperature change at around 2 °C (above preindustrial levels) within the 21st century without overshooting (i.e. maintaining the temperature at this target value once attained). The second scenario considers reaching a target of around 1.5 °C in 2100 with overshooting. We assumed the same trajectory of GHG emissions in both scenarios until the middle of the century to reflect the difficulty in reducing emissions in the near term beyond those needed to achieve the 2 °C target. Such difficulty is reinforced in a world with strong climatic response to increased GHG concentrations, which means it is hard to stabilize the temperature rise at 1.5 °C without overshoot. As populations grow wealthier by the middle of the century and concerns regarding the impacts of climate change spread, the global society could opt for one of two alternative paths: stabilizing global temperature change at current levels (2 °C scenario), or enhancing mitigation efforts to achieve a lower level of global warming (1.5 °C scenario). Details regarding the scenarios and the preparation of the ESM inputs are provided in sections 1.2 and 1.3 of SI.

2.3. Climate model and analyzed variables
The experiments were performed using the MIROC-ESM (Watanabe et al 2011), which has been used previously in analysis based on RCPs (Hajima et al 2012). Among the Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Taylor et al 2012), this model has a high-end ECS of 4.7 K (Andrews et al 2012), with near average carbon-concentration feedback and strong carbon-climate feedback (Arora et al 2013). Thus, the results represent low-end allowable (compatible) emissions projected for the future with RCPs (Jones et al 2013). The model also has a high transient climate response (TCR) of 2.2 K (Flato et al 2013), and high TCR to cumulative CO₂ emissions (TCRE) of 2.2 K/1000GtC (Gillet et al 2013).

In this study, the mean of three ensemble members for each scenario was used for analysis to reduce the effect of interannual variability. Each member started from a different initial condition, i.e. three different years with 10 year intervals that were taken from a ‘control run’ (run with non-evolving pre-industrial conditions, i.e. prescribed atmospheric concentrations as well as unperturbed land use). The ESM used a T42 (128 × 64) grid system.

Here we examined the variables of surface air, ocean mixed layer and all ocean layers. For surface air we focused on GMST and precipitation, as well as vegetation productivity (gross primary production, GPP). For the ocean mixed layer, we looked at SST and two widely-used indicators closely related to that: Arctic sea ice and coral bleaching (using degree heating month following Donner (2009) and Frieler et al (2013)). For whole ocean warming we estimated sea level rise (SLR) due to steric changes in the Pacific Island region, which is considered the most vulnerable region to SLR. Because it is difficult for current ESMs to accurately represent all components of SLRs, we only focused on steric change and the spatial difference of SLR. Here, the spatial heterogeneity in SLR (difference of local value from global mean) is a result of the changes in the local conditions of surface wind, ocean current, temperature and salinity. These indicators were also analyzed by Schleussner et al (2016).

We used GPP instead of yield projections because our ESM did not include a sophisticated crop model. Descriptions of the methods used to evaluate GMST, SLR and coral bleaching, as well as to remove the model drift are presented in SI.

3. Results
3.1. Emission pathways
CO₂ emissions from FFI (figure 1(a)) decreased sharply from the year of climate policy implementation (2020). In 2100, FFI CO₂ emissions reached
negative values and Kyoto GHG emissions in 2050 dropped to very low levels (5 GtCO₂eq, not shown in figure). As global temperature peaked, emissions in the 2 °C scenario increased slightly, followed by a decrease and stabilization later in the century. This fluctuating trend ensured that temperature remained constant at the target value (2 °C). From 2050, emissions in the 1.5 °C scenario decreased consistently, reaching around −24 GtCO₂ FF in 2100, and after that they returned to near zero. Cumulative CO₂ emissions in the 21st century showed a clear contrast between the two scenarios after 2050, mainly driven by the large penetration of negative emission technologies (biomass with CCS). In the 2 °C scenario, cumulative emissions for the period 2010–2100 were 358 GtCO₂, whereas in the 1.5 °C scenario, they reached −337 GtCO₂ (figure 1(b), but note that the figure shows the value from 1850). The latter value fell outside the range indicated in studies compiling scenarios consistent with the 1.5 °C target (Millar et al 2017, IPCC 2018). The suitability of this outcome was evaluated against the limits for carbon sequestration. The cumulative carbon sequestration between 2010 and 2100 in our analysis was between 2320 and 2485 GtCO₂ (figure S2(e)), which is slightly above the central value of global sequestration potential indicated in the literature (IPCC 2005). The cumulative carbon emissions for 2010–2300 were −53 GtCO₂ and −936 GtCO₂ for the 2 °C and 1.5 °C scenarios. The carbon price increased to around 800 USD/tCO₂ by 2080 for the 1.5 °C scenario, and for the 2 °C scenario it fluctuated between 200 and 350 USD/tCO₂ after 2050 and stabilized around 250 USD/tCO₂ by 2080 (see figure S2(d)).

3.2. Surface air
Time series of the GMST change from preindustrial levels for the two scenarios are shown in figure 1(c). After the scenarios diverged in 2050, the temperature anomalies became slightly too large (by around 0.2 °C shortly after 2050, diminishing to 0.1 °C in the first half of the 22nd century) compared with the targets under both scenarios, although a gradual decrease in temperature means the original targets were met in the 23rd century. GMST changes, considering the change in observation coverage and the change in global mean surface air temperature, are presented in SI. The atmospheric CO₂ concentration (pCO₂) presented in figure 1(d) peaked around 2040 at 450 ppm for both scenarios. For the 2 °C scenario, pCO₂ decreased almost steadily to 370 ppm in 2250. For the 1.5 °C scenario, a rapid decrease to 350 ppm occurred before 2100, and then there was a steady decrease to around 320 ppm in 2250 at a rate similar to the 2 °C scenario.

The relationship between the total temperature anomaly and cumulative CO₂ emissions is presented in figure S3 (in SI). When including non-CO₂ warming, the ratio of temperature rise to cumulative emissions (TCRE) increased in the overshoot scenario, but when considering only CO₂-induced warming, changes in TCRE, estimated using a simple climate model, were much smaller (with around a 10% increase in the period of decreasing temperature in the 1.5 °C
Considerable geographical heterogeneity, which was similar for these three periods, was found in the temperature difference between the 1.5 °C and 2 °C scenarios. There were large positive (larger in the 2 °C scenario) differences over land in the Northern Hemisphere; however, the difference in the region of the Southern Ocean was small, and it was actually negative in some parts of the Southern Ocean in 2281–2300 (figure 2(c)). There were relatively large positive differences in dryland areas (including Central Asia, Southwest Africa and Australia) and the tropical rainforest around the Amazon. The considerable difference in the northern high-latitude region was considered the result of ice-albedo feedback (i.e. the so-called polar amplification). In both scenarios, strong ice-albedo feedback resulted in a large temperature rise in this region, while the difference between the scenarios was also enhanced. The small difference in the Southern Ocean region (40°–60° S) was considered an outcome of the large heat capacity of the surface water associated with the deep mixed layer in combination with the absence of land at such latitudes.

The geographic distribution of the difference of temperature between the 2 °C and 1.5 °C scenarios is shown in figures 2(a)–(c). Here, averages of three 20-year periods corresponding to the end of the IAM scope (2091–2110), and the ends of the 22nd (2191–2210) and 23rd (2281–2300) centuries are presented. Considerable geographical heterogeneity, which was similar for these three periods, was found in the temperature difference between the 1.5 °C and 2 °C scenarios. There were large positive (larger in the 2 °C scenario) differences over land in the Northern Hemisphere; however, the difference in the region of the Southern Ocean was small, and it was actually negative in some parts of the Southern Ocean in 2281–2300 (figure 2(c)). There were relatively large positive differences in dryland areas (including Central Asia, Southwest Africa and Australia) and the tropical rainforest around the Amazon. The considerable difference in the northern high-latitude region was considered the result of ice-albedo feedback (i.e. the so-called polar amplification). In both scenarios, strong ice-albedo feedback resulted in a large temperature rise in this region, while the difference between the scenarios was also enhanced. The small difference in the Southern Ocean region (40°–60° S) was considered an outcome of the large heat capacity of the

Figure 2. Difference of temperature, precipitation and land gross primary production between 2 °C and 1.5 °C scenarios. Averages of temperature difference (°C) in (a) 2091–2110, (b) 2191–2210 and (c) 2281–2300. (d)–(f) The same as (a)–(c) but for precipitation: ([PR_c − PR_a]/PR_a, where PR_c and PR_a is precipitation of the 2 °C and 1.5 °C scenarios, respectively. (g)–(i) The same as (a)–(c) but for gross primary production (GPP) between 1.5 °C (GPP_2) and 2 °C (GPP_1) scenarios. Averages of GPP_2 − GPP_1 are presented.
correlation, they were cancelled to some extent, but the stronger effect of precipitation was evident. Northern high latitudes have the unique response of a positive relationship to temperature in 2091, and weak negative relationship to both temperature and precipitation in 2191–2210 and in 2281–2300.

3.3. Ocean mixed layer
The SST change (figure 3(a)) showed a smaller but similar trajectory to GMST, which was reflected in the change in Arctic Sea ice (figure 3(b)). Under the 1.5°C scenario, in some years ice remained in the ice-minimum season (August/September) after 2100, in contrast to the 2°C scenario. The annual mean also showed some difference between scenarios after 2100.

The results on coral bleaching are presented in figure 3(c). Broadly, the results were comparable to both Frieler et al. (2013) and Schleussner et al. (2016), but there were several important differences. (1) In the no-thermal adaptation (by corals) case, the increase in the fraction of grids exceeding coral thermal tolerances reached close to 1 earlier (before the 1.5°C and 2°C scenarios diverged) in our study. (2) In the no-thermal adaptation case, the 1.5°C scenario maintained the fractional value at around 0.9 until 2300. (3) In the adaptation case, the peak fractional value (~0.8 in both scenarios) was higher in our study in comparison with Frieler et al. (2013) and Schleussner et al. (2016), as summarized in table S5. In addition, we also tested weaker thermal adaptation cases (figure S7).

3.4. Total ocean heat uptake and SLR
Figures 4(a), (b) shows annual and cumulative OHU, respectively. Even by 2300, OHU decreased but remained positive under both scenarios; thus, the cumulative OHU (or change in ocean heat content) kept increasing up to that year. The decrease in OHU canceled the decrease in CO2-induced radiative forcing, resulting in stabilized atmospheric temperature.

Figure 4(c) shows the steric effect and spatial heterogeneity of SLR (as estimated by ESMs) in Pacific Island regions (0°–23° S, 150° E–165° W; relative to the 2006–2015 average). Not surprisingly, global mean steric part of SLR directly reflected the change in cumulative OHU. Although the difference of local and global mean SLR seemed to stabilize in the first half of the 22nd century, this was not the case for the steric element (by increasing cumulative OHU; see figure 4(b)). The difference in the sum of the two terms between the scenarios was small (1.5 cm) in 2100, but it increased gradually to 6.5 and 9.1 cm in 2200 and 2300, respectively.

![Figure 3](image1.png)

**Figure 3.** Changes in sea surface temperature and related indicators. (a) Time series anomalies in sea surface temperature from 1850 to 1869 average, (b) annual mean, maximum and minimum (monthly) Arctic sea ice concentration (70°–90° N), (c) difference in impact on coral reefs between 2°C and 1.5°C scenarios. Fraction of grids including coral reefs that experience three or more periods of DHM ≥ 2 (in four consecutive months) in each decade. For 1.5°C (red) and 2°C (black) scenarios, no thermal adaptation (solid lines) and thermal adaptation of 0.4°C DHM/decade cases (dashed lines) are indicated with average, maximum and minimum values among the three ensemble members.

![Figure 4](image2.png)

**Figure 4.** Changes in global ocean heat uptake and in sea level rise in the Pacific Island region. (a) Ocean heat uptake, (b) cumulative ocean heat uptake (from 2006), (c) sea level rise in Pacific Island region (0°–23° S, 150° E–165° W; relative to 1986–2005 average), considering only geographical heterogeneity and global mean steric change. Red and black curves represent output from 1.5°C and 2°C scenarios, respectively.
4. Discussion

The spatial distribution of surface air temperature indicated that the conditions related to Arctic sea ice are significantly different between the two scenarios in spite of overshoot. Previous studies (Li et al 2013, Hoegh-Guldberg et al 2018, Jahn 2018) claimed that an intermediate temperature overshoot had no long-term consequences for Arctic sea ice coverage. In our experiments, Arctic sea ice coverage is, to a large degree, determined by the GMST (a very small scenario-dependence was apparent in plotting the 10-year averages (figure S8)). Shu et al (2015) and Rosenblum and Eisenman (2017) indicated all CMIP5 models including MIROC-ESM underestimate the decreasing trend in Arctic sea ice. Hoegh-Guldberg et al (2018) indicated (with medium confidence) that there will be at least one sea ice-free Arctic summer after about 10 years of stabilized warming at 2 °C, while about 100 years are required at 1.5 °C. Our results show for 2100–2300 with 1.5 °C scenario we had zero values for the minimum ice coverage once in a decade.

Ecosystem-related indicators are not necessarily easily inferable from the GMST trajectory. SR1.5 summarizes the literature as a decline in coral reefs by approximately 70%–90% and 99% under the 1.5 °C and 2 °C scenarios, respectively (high confidence). Our findings were similar for the 2 °C scenario case, and worse in the 1.5 °C case. In the overshoot period, once the temperature anomaly reached 2 °C, almost all corals became at risk. For the 1.5 °C case, once the fraction of grids at risk was close to 1, the benefit of a subsequent small decrease was questionable, although for the non-overshoot case, an increase in SST that might cause coral bleaching and mortality was 25% less likely to occur under 1.5 °C warming than 2 °C warming (King et al 2017). Although here we used 0.4 °C (degree heating months; DHM) following Friel et al (2013) and Schleussner et al (2016), they noted that the thermal adaptation value appeared very ambitious given the long creation times of reef-building corals and the consequently slow rate at which evolutionary adaptation occurs. Figure S7 reveals that even a thermal adaptation of 0.1 °C (DHM/decade) resulted in a large impact—increase in survival rate—but still most corals are projected to be critically damaged during the overshoot period. In addition, Baker et al (2008) indicated that recovery within five years was too optimistic.

For land GPP, an increase of several percent was found under the 2 °C scenario in most regions. The increase in GPP in northern high-latitude regions and globally was consistent with Tanaka et al (2017) who found a 5% and 14% NPP increase for 0.5 °C rise in GMST. A 5% and 8%–10% (depending on the periods) GPP increase was found in the 2 °C compared with the 1.5 °C scenario in the current study. For crop yields, Schleussner et al (2016) highlighted that substantial uncertainty renders differentiation between the effects of 1.5 °C and 2 °C warming difficult in most regions in cases where CO2 fertilization is not removed. Iizumi et al (2017) found lower maize and soybean yields, higher rice production and no clear difference for wheat on a global mean basis under 2 °C warming in comparison with 1.5 °C warming.

The cumulative OHU was significantly impacted by overshooting, because once warmed up the deep ocean cannot be cooled even if the atmospheric (and ocean mixed layer) temperature decreases. The small difference in steric SLR before 2100 could be explained by overshooting. As heat is absorbed by the ocean, while the temperature is high, the SLR was considered to be higher in the overshoot scenario than in the case without overshooting. It should be noted that the change in steric SLR slowed but remained positive during the temperature-decreasing period.

Although the SLR in this study only included the steric component and excluded additional elements such as the freshwater supply from glaciers, Greenland and the Antarctic ice sheets, and land water storage, the geoid and isostasy, the results are consistent with SLR values reported in the literature. For instance, the contribution of thermal expansion, considered to be the primary part of the steric change, in historical SLR change is estimated at around 1/3–1/2 based on observations and modeling (historical and RCP2.6 scenario runs) (Church et al 2013). Future SLR and the contribution of thermal expansion from 1986–2005 to 2081–2100 have been projected as 40 (26–55) cm and 14 (10–18) cm, respectively (Church et al 2013). In this study, the contribution of steric change over the same period was 17 (18) cm under the 1.5 °C (2 °C) scenario. Also, based on the fraction of future contribution by thermal expansion suggested by Church et al (2013), our result is consistent with Schleussner et al (2016) who reported SLR values (considering freshwater supply and surface mass balance) from 2000 to 2100 of 41 (29–53 for 66% range) cm and 50 (36–65) cm for 1.5 °C and 2 °C scenarios, respectively. Perrete et al (2013) reported large uncertainty in the estimation of non-steric SLR, but the difference in non-steric SLR between the 1.5 °C and 2 °C scenarios is predicted to be small (because the difference between 1.5 °C and 2 °C scenarios is less than that of RCP2.6 and RCP4.5 they analyzed). Thus, the difference in total SLR, at 2100, between the two scenarios is also expected to be small (probably 2–3 cm). SR1.5 concluded that the difference in global mean SLR between the 1.5 °C and 2 °C scenarios was around 0.1 m, which was bigger than this study (possibly attributable to our consideration of the overshooting scenario for the 1.5 °C target).

The emission pathways in the second half of the century to move from the 2 °C to the 1.5 °C target in this study (see figure 1(a)) showed considerably aggressive carbon emission reductions. This is in stark contrast with other studies that have characterized the difference between the 2 °C and 1.5 °C targets with
earlier cuts in GHG emissions, which lead more quickly to net zero emissions (Rogelj et al. 2015, Sanderson et al. 2016, Schleussner et al. 2016, Millar et al. 2017). This difference was enhanced by the features of the ESM used in this study, which characterized the Earth system with higher climate sensitivity and stronger carbon-climate feedback (i.e. high TCRE) compared with the parameters of the climate models used in most emission scenario analysis. Hence, allowable anthropogenic GHG emissions consistent with a given climate target are lower.

In this study, for simplicity we tuned MAGICC in GCAM-SOUSEI only by varying ECS. The tuning represented the relationship between CO₂ emissions and the GMST change, and the representation of carbon cycle related variables was not considered important. Figure S9 presents a reasonable representation in land and ocean carbon uptake each year, but their cumulative values were smaller in MIROC-ESM, leading to the consequently higher pCO₂ in that model. By cancelling the difference between MIROC-ESM and GCAM-SOSEI with that in the sensitivity of temperature to pCO₂, the resultant relationship of CO₂ emissions and the GMST change became similar between the two models. Our simple climatic model (even simpler than MAGICC), the simple climate model for optimization (SCM4OPT) (Su et al. 2017, 2018), tuned with physical and carbon cycle parameters, indicated a lack of tuning in the carbon cycle alone may not explain the higher temperature in the 1.5 °C scenario at 2100 (see red line in figure S11(a)).

There are several possibilities within the socio-economic system leading to pathways equally consistent with the 1.5 °C and 2 °C targets. Major factors include, but are not limited to, population and GDP projections, availability and progress of mitigation options, resource availability, geographic and sectoral scope of policy implementation. In fact, these scenarios represent idealized futures where climate polices are implemented in all regions simultaneously, neglecting any delay or heterogeneity in mitigation efforts.

5. Conclusions

Experiments using an ESM with 2 °C stabilization and 1.5 °C with overshooting scenarios were performed using socioeconomically feasible emission and land use pathways. The two scenarios followed the same pathway up to 2050, when the temperature anomaly reached 2 °C, and then diverged. In this study, the scenarios were designed using an IAM coupled with a simplified climate model tuned for the ESM. The emission pathways obtained for 1.5 °C and for 2 °C targets had quite large differences in terms of cumulative CO₂ emissions in the 21st century (2010–2100). The GMST trajectories resulted in values for 2100 that were somewhat delayed in comparison with those expected under the Paris Agreement.

The ESM output revealed significant differences between the scenarios in terms of impact on surface air and ocean mixed layer. Arctic sea ice recovery—from sea-ice-free conditions in summer—occurred only under the 1.5 °C scenario. Ecosystem-related indicators were more complicated; land GPP was larger in the 2 °C scenario through higher atmospheric CO₂ concentration and greater precipitation, while for coral bleaching, the possibility of corals surviving this century under either scenario was small. In an indicator related to total OHU, the effect of overshooting was non-negligible. For SLR, the difference between the 1.5 °C and 2 °C scenarios due to the steric change and the regional anomaly was only 1.5 cm, smaller than previous studies have indicated until 2100, due to large total OHU in overshooting, but the difference gradually increased to 6.5 cm and 9.1 cm in 2200 and 2300, respectively.

Overall, we found that the difference between 1.5 °C and 2 °C was large in indicators related to surface air or ocean mixed layer, but overshooting the 1.5 °C target by 0.5 °C could diminish the significance of several impact indicators related to total OHU, or to the ecosystems. It should be also noted that even for the 1.5 °C case, the difference from present conditions is quite large (for all aspects we examined in this study including land GPP, Arctic Sea ice, coral bleaching, and SLR). The characteristics of the model used here, including large values in equilibrium climate sensitivity, transient climate response and transient climate response to cumulative CO₂ emissions, might have some influence on the results as well as limiting the feasibility of a 1.5 °C scenario without overshoot. Although, to draw robust conclusions, similar studies using other models will be needed, the results shown here have important implications regarding the revision of emission reduction targets. This outcome is based on an IAM tuned to a particular ESM; it highlights the importance of combining such approaches (IAM and ESM) for assessing practical issues.

Acknowledgments

The authors thank Dr M Watanabe of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) for helpful comments, Dr T Hajima of JAMSTEC for supporting the ESM experiments, H Takayama for help in calculating the global mean temperatures and Dr Y Le Page for kindly adjusting his land use downscaling tool for the purposes of our study. This research was supported by the ‘Integrated Research Program for Advancing Climate Models (TOUGOU program)’ of the Ministry of Education, Culture, Sports, Science and Technology, Japan.
Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Andrews T, Gregory J M, Webb M J and Taylor K E 2012 Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models Geophys. Res. Lett. 39 109711.

Azar C, Johansson D J A and Mattsson N 2013 Meeting global temperature targets—the role of bioenergy with carbon capture and storage Environ. Res. Lett. 8 034004.

Baker A C, Glynn P W and Rieg B 2008 Climate change and coral reef bleaching: an ecological 41 assessment of long-term impacts, recovery trends and future outlook Estuarine, Coast. Shelf Sci. 80 435–71.

Church J A et al 2013 Sea level change Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T F Stocker et al (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press) ch 9 pp 741–866.

Donner S D 2009 Coping with commitment: projected thermal stress on coral reefs under different future scenarios PalaeoOne 4 e5712.

den Elzen M G J and van Vuuren D P 2007 Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs Proc. Natl Acad. Sci. 104 17931–6.

Flato G et al 2013 Evaluation of climate models Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T F Stocker et al (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press) ch 9 pp 741–866.

Frieler K et al 2013 Limiting global warming to 2 °C is unlikely to save most coral reefs Nat. Clim. Change 3 165–70.

Gattuso J-P et al 2015 Segmenting futures for ocean and society from different anthropogenic CO2 emissions scenarios Science 349 aa4722.

Gillett N P, Arora V K, Matthews D and Allen M R 2013 Constraining the ratio of global warming to cumulative CO2 emissions using CMIP5 simulations J. Clim. 26 6844–58.

Hajima T, Ise T, Tachiiri K, Kato E, Watanabe S and Kawamiya M 2012 Climate change, allowable emission, and earth system response to representative concentration pathway scenarios J. Met. Soc. Japan. 90 417–34.

Hoegh-Guldberg O et al 2018 Impacts of 1.5 °C global warming on natural and human systems Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty ed V Masson-Delmotte et al (Geneva, Switzerland: World Meteorological Organization) p 32.

Jahn A 2018 Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming Nat. Clim. Change 8 409–13.

Jones G D et al 2013 21st century compatible CO2 emissions and airborne fraction simulated by CMIP5 earth system models under 4 representative concentration pathways J. Clim. 26 4398–413.

Kim S H et al 2006 The objECS framework for integrated assessment: hybrid modeling of transportation Energy J. 27 63–91.

King A D, Karoly D J and Henley B J 2017 Australian climate extremes at 1.5 °C and 2 °C of global 35warming Nat. Clim. Change 7 412–6.

Li C, Notez D, Tietsche S and Marotzke J 2013 The transient versus the equilibrium response of sea ice to global warming J. Clim. 26 5624–36.

Mathiesius S, Hofmann M, Caldeira K and Schellnhuber H J 2015 Long-term response of oceans to CO2 removal from the atmosphere Nat. Clim. Change 5 107–13.

Meinshausen M, Raper S C B and Wigley T M L 2011 Emitting coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6. I. Model description and calibration Atmos. Chem. Phys. 11 1417–56.

Millar R J et al 2017 Emission budgets and pathways consistent with limiting warming to 1.5 °C Nat. Geosci. 10 741–7.

Mitchell D et al 2016 Realizing the impacts of a 1.5 °C warmer world Nat. Clim. Change 6 735–7.

O’Neill B C et al 2016 The scenario model intercomparison project (ScenarioMIP) for CMIP6 Geosci. Model Dev. 9 3461–82.

Palter JB, Frölicher TL, Paynter D and John G 2018 Climate, ocean circulation, and sea level changes under stabilization and overshoot pathways to 1.5 K warming Earth Syst. Dyn. 9 197–928.

Perrette M, Landerer F, Riva R, Frieler K and Meinshausen M 2013 A scaling approach to project regional sea level rise and its uncertainties Earth Syst. Dyn. 4 11–29.

Ricke K L, Millar R J and MacMartin D G 2017 Constraints on global temperature target overshoot Sci. Rep. 7 14743.

Rogelj J et al 2015 Energy system transformations for limiting end-of-century warming to below 1.5 °C Nat. Clim. Change 5 319–27.

Rogelj J et al 2018 Scenarios towards limiting global mean temperature increase below 1.5 °C Nat. Clim. Change 8 325.

Rosenblum E and Eisenman I 2017 Sea ice trends in climate models only accurate in runs with biased global warming J. Clim. 30 6265–78.

Sanderson B M et al 2017 Community climate simulations to assess avoided impacts in 1.5 and 2 °C futures Earth Syst. Dyn. 8 827–47.

Sanderson B M, O’Neill BC and Tebaldi C 2016 What would it take to achieve the Paris temperature targets? Geophys. Res. Lett. 43 7133–42.

Schellnhuber H J, Rahmstorf S and Winkelmann R 2016 Why the right climate target was agreed in Paris Nat. Clim. Change 6 649–53.

Schlesser C F et al 2016 Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C Earth Syst. Dyn. 7 327–51.

Shiogama H 2017 Climate projections for the 1.5 °C and 2.0 °C targets Environ. Inf. Sci. 46 281–4 (in Japanese).

Shu Q, Song Z and Qiao F 2015 Assessment of sea ice simulations in the CMIP5 models Cryosphere 9 399–409.

Su X, Shiogama H, Tanaka K, Fujimori S, Hasegawa T, Hijikya Y, Takahashi K and Liu J 2018 How do climate-related uncertainties influence 2 and 1.5 °C pathways? Sustain. Sci. 13 291.

Su X, Takahashi K, Fujimori S, Hasegawa T, Tanaka K, Kato E, Shiogama H, Masui T and Emori S 2017 Emission pathways to achieve 2.0 °C and 1.5 °C climate targets Earth’s Future 5 592–604.

Tanaka A et al 2017 On the scaling of climate impact indicators with global mean temperature increase: a case study of emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty ed V Masson-Delmotte et al (Geneva, Switzerland: World Meteorological Organization) p 32.
terrestrial ecosystems and water resources Clim. Change 141
775–82
Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5
and the experiment design Bull. Am. Meteorol. Soc. 93 485–98
Thomson A M et al 2011 RCP4.5: a pathway for stabilization of
radiative forcing by 2100 Clim. Change 109 77
Tokarska K B and Zickfeld K 2015 The effectiveness of net negative
carbon dioxide emissions in reversing anthropogenic climate
change Geophys. Res. Lett. 10 094013
Tsutsui J et al 2007 Long-term climate response to stabilized and
overshoot anthropogenic forcings beyond the twenty-first
century Clim. Dyn. 28 199–214
van Vuuren D P et al 2011 RCP2.6: exploring the possibility to keep
global mean temperature increase below 2°C Clim. Change
109 95–116
van Vuuren D P et al 2018 Alternative pathways to the 1.5°C target
reduce the need for negative emission technologies Nat. Clim.
Change 8 391
Watanabe S et al 2011 MIROC-ESM 2010: model description and
basic results of CMIP5-20c3m experiments Geosci. Model
Dev. 4 845–72
Zickfeld K, Arora V K and Gillett N P 2012 Is the climate response
to CO₂ emissions path dependent? Geophys. Res. Lett. 39
L05703