



How do climate-related uncertainties influence 2 and 1.5 °C pathways?

Xuanming Su¹ · Hideo Shiogama² · Katsumasa Tanaka² · Shinichiro Fujimori^{1,3} · Tomoko Hasegawa^{1,4} · Yasuaki Hijioka¹ · Kiyoshi Takahashi¹ · Jingyu Liu¹

Received: 20 September 2017 / Accepted: 15 December 2017
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Abstract

We investigate how uncertainties in key parameters in the carbon cycle and climate system propagate to the costs of climate change mitigation and adaptation needed to achieve the 2 and 1.5 °C targets by 2100 using a stochastic version of the simple climate model for optimization (SCM4OPT), an integrated assessment model. For the 2 °C target, we find a difference in 2100 CO₂ emission levels of 20.5 GtCO₂ (− 1.2 GtCO₂ to 19.4 GtCO₂), whereas this difference is 12.0 GtCO₂ (− 6.9 GtCO₂ to 5.1 GtCO₂) for the 1.5 °C target (17–83% range). Total radiative forcing in 2100 is estimated to be 3.3 (2.7–3.9) Wm^{−2} for the 2 °C case and 2.5 (2.0–3.0) Wm^{−2} for the 1.5 °C case. Carbon prices in 2100 are 482 (181–732) USD(2005)/tCO₂ and 713 (498–1014) USD(2005)/tCO₂ for the 2 and 1.5 °C targets, respectively. We estimate GDP losses in 2100 that correspond to 1.9 (1.2–2.5)% of total gross output for the 2 °C target and 2.0 (1.5–2.7)% for the 1.5 °C target.

Keywords Climate change · Climate-related uncertainties · Socioeconomic scenarios · Carbon prices · Mitigation costs · Adaptation costs

Introduction

The Paris Agreement aims to hold the global temperature rise in this century to well below 2 °C relative to pre-industrial levels and to pursue efforts to limit the temperature

increase to 1.5 °C. Integrated assessment models (IAMs), which account for the interactions among the socioeconomic and physical aspects of climate change, are used to explore emission pathways for achieving climate change targets. Considerable uncertainties surround IAMs regarding both socioeconomics and climate science (Rotmans and van Asselt 2001; van Asselt and Rotmans 2002; Heal and Millner 2014; Gillingham et al. 2015). In terms of these socioeconomic aspects, recent IAM studies have investigated uncertainties stemming from socioeconomic impacts, technological change, and discount rates (Rotmans and van Asselt 2001; van Asselt and Rotmans 2002; van den Bergh and Botzen 2014, 2015; Gillingham et al. 2015; Metcalf and Stock 2015; Weyant 2017). However, the focus is usually placed on limited sources of uncertainty in the physical climate aspects. For instance, three IAMs that are widely used to evaluate the social cost of carbon, DICE (Nordhaus and Sztorc 2013; Nordhaus 2013, 2014), FUND (Anthoff et al. 2011), and PAGE (Hope 2011, 2013) address primarily the uncertainty in (equilibrium) climate sensitivity. Other sources of uncertainty, including those arising from the carbon cycle and the effects of aerosols, are not considered explicitly in these IAMs.

Handled by Seita Emori, National Institute for Environmental Studies, Japan.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s11625-017-0525-2>) contains supplementary material, which is available to authorized users.

✉ Xuanming Su
suxuanming@gmail.com

- ¹ Center for Social and Environmental Systems Research, National Institute for Environmental Studies (NIES), Tsukuba, Japan
- ² Center for Global Environmental Research, National Institute for Environmental Studies (NIES), Tsukuba, Japan
- ³ Energy Program, International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria
- ⁴ Ecosystem Services and Management Program, International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria

In this study, we employ the simple climate model for optimization (SCM4OPT) (Fujimori et al. 2016, Su et al. 2017), an IAM that considers a full suite of greenhouse gases, pollutants, and aerosols. Here, we probe the uncertainties arising from various physical and biogeochemical processes, using sets of parameter estimates obtained from model emulations. As a note of caution, this analysis does not address potentially larger uncertainties that can be seen from observational constraints based on inversion approaches (Tanaka et al. 2009; Bodman et al. 2013). We consider only uncertainties that result from physical climate processes and hold the socioeconomic parameters constant. The objectives of this study are (1) to evaluate emission pathways that limit the temperature increase to below 2 °C or 1.5 °C after 2100 while considering several sources of climate-related uncertainties and (2) to explore how such climate-related uncertainties are translated into uncertainties

in socioeconomic quantities, such as carbon prices, mitigation costs, adaptation costs, and GDP losses.

Methodology

Model description

SCM4OPT consists of a socioeconomic module and a simple climate module (Fig. 1). The socioeconomic module is calibrated to represent the Shared Socioeconomic Pathways 2 (SSP2) scenario (Fujimori et al. 2017, Su et al. 2017). We select the Asia–Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE) (Fujimori et al. 2014a, b, 2017), which is one of the IAMs that can implement the SSPs, for use in our working team. We use this model to generate the SSP2 assumptions based on the SSP narratives

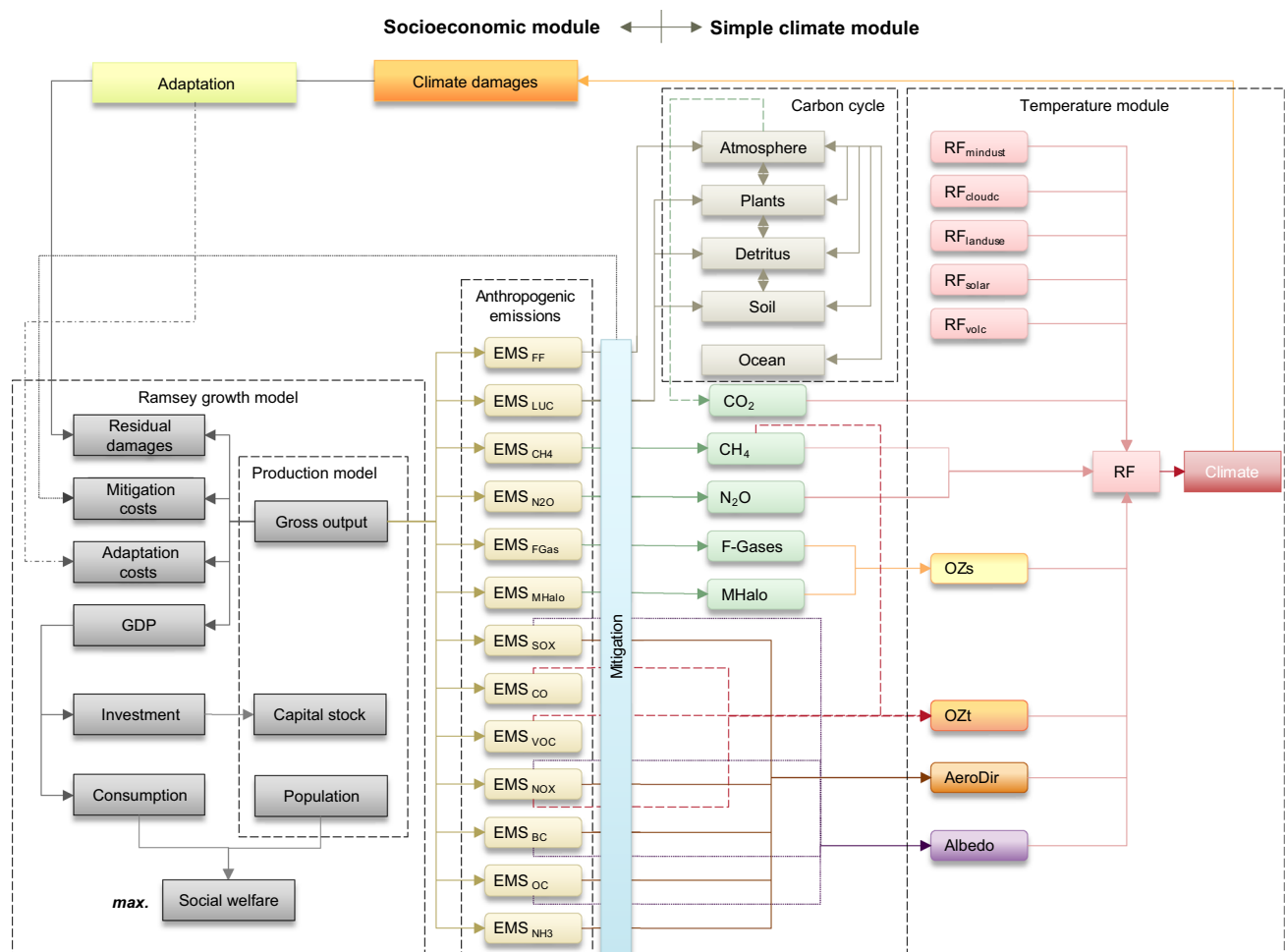


Fig. 1 SCM4OPT model structure. The abbreviations shown in this figure are as follows. *AeroDir* direct forcing effects from aerosols, *cloudc* cloud cover, *EMS* emissions, *FF* fossil fuels, *GDP* gross domestic product, *LUC* land-use change, *max* maximize, *MHalo* hal-

ogenated gases regulated under the Montreal Protocol, *min dust* mineral dust, *OZs* stratospheric ozone, *OZt* tropospheric ozone, *RF* radiative forcing, *volc* volcanic

to ensure model consistency with our earlier study (Su et al. 2017), although AIM/CGE was used to produce the marker scenario of SSP3. As in the DICE-2013R model (Nordhaus and Satorc 2013; Nordhaus 2013), the global gross production output is defined using a constant-returns-to-scale Cobb–Douglas production function (Cobb and Douglas 1928; Douglas 1976), considering capital, population, and Hicks-neutral technological change (Hicks 1966). The gross output is, therefore, distributed into GDP, adaptation costs, mitigation costs, and residual damages that result from feedbacks on climate change. We maximize the total social welfare, a discounted sum of the utility of per capita consumption, weighted by population. The approach used here is based on the Ramsey economic growth model (Ramsey 1928). We endogenously account for the emission abatements of not only industrial CO₂, but also land-use CO₂, CH₄, N₂O, halogenated gases, CO, volatile organic compounds (VOCs), SO_x, NO_x, black carbon (BC), and organic carbon (OC) through the use of individual marginal abatement cost (MAC) curves. The abatement levels of non-CO₂ components are defined as a power function of control levels of industrial CO₂ emissions that is based on a sensitivity analysis of the SSP2 scenario (Su et al. 2017). Therefore, the abatement costs and the carbon prices are attributed only to reductions in industrial CO₂ emissions in this study. Negative CO₂ emissions from industrial sources can be realized through carbon capture and storage (CCS). The land-use emissions considered here include CO₂ emissions from land use and land-use changes, including pasture conversion, deforestation, afforestation, reforestation, and soil management (Fujimori et al. 2017, Su et al. 2017). The net land-use emissions are determined by the base case emissions subtracting the abated amount that relates to the reduction level of industrial CO₂ emissions [see Eqs. (4–5) in the Supporting Information of Su et al. (2017)]. The resulting net emissions are fed into the simple climate module to calculate the radiative forcing and the global mean temperature (GMT) change relative to pre-industrial levels. The simple climate module is largely consistent with MAGICC 6.0 (Meinshausen et al. 2011a, b), except for a few processes that are simplified in SCM4OPT. For instance, we use a two-box temperature module to estimate the GMT, instead of the upwelling-diffusion climate model used in MAGICC 6.0. Therefore, the ocean heat uptake is not explicitly considered in this study. We estimate the climate change damages using a damage function related to the GMT increase and consider both mitigation and adaptation options:

$$\Delta_{\text{gross}}(t) = Y_{\text{gross}}(t)(a_1 T(t) + a_2 T(t)^{a_3}), \quad (1)$$

where $\Delta_{\text{gross}}(t)$ is the gross damage, $Y_{\text{gross}}(t)$ represents the gross output, and $T(t)$ denotes the GMT. The t stands for annual time. The parameters a_1 , a_2 , and a_3 are estimated to be 0.0005, 0.0025, and 2.2523, respectively (Su et al. 2017).

Uncertainties

Our analysis accounts for the uncertainties in a total of 35 key physical and biological parameters that represent the inter-model differences among 10 C⁴MIP carbon cycle models and 20 CMIP3 AOGCMs (Tables S1–S4). Broadly, our approach is as follows. For processes that are consistent with MAGICC6, we adopt the values of the associated parameters estimated for MAGICC6 to emulate the inter-model comparison results. On the other hand, for processes that are simplified from MAGICC6, we tune the associated parameters to provide a best fit to the emulation results from MAGICC6.

More specifically, 30 parameters (nos. 1–30 in Tables S1–S3) are adjusted to mimic the output from MAGICC 6.0 for each C⁴MIP carbon cycle model, namely, BERN, CCSM1, CLIMBER, FRCGC, HADLEY, IPSL, LLNL, MPI, UMD2, and UVIC. Two parameters related to CO₂ fertilization (nos. 23–24 in Table S2) and six parameters used to calculate human-induced regrowth of the land biosphere (nos. 25–30 in Table S3) are tuned to provide a best fit to each of the emulated atmospheric CO₂ concentration pathways extending to 2100 from MAGICC 6.0. All of the other carbon cycle parameters are assumed to be the same as those used in MAGICC 6.0 (nos. 1–22 in Table S1). The calibration results for atmospheric CO₂ concentrations are shown in Figure S1. The mean temporal evolution of the CO₂ concentrations is similar between MAGICC6.0 and SCM4OPT, but the uncertainty ranges are relatively large in the latter, due to the simplified treatments of CO₂ fertilization effects and land-use emissions due to regrowth used in that model. For instance, the emulation results of CO₂ concentration in 2100 generated by SCM4OPT are 441⁺⁴⁷₋₃₅, 565⁺⁸⁰₋₆₄, 700⁺⁹⁸₋₉₃, and 961⁺¹²⁹₋₁₄₅ parts per million (ppm) for the Representative Concentration Pathway (RCP) scenarios RCP3PD, RCP4.5, RCP6, and RCP8.5 (Vuuren et al. 2011; Thomson et al. 2011; Masui et al. 2011; Riahi et al. 2011), respectively (the subscript and superscript numbers indicate the 17–83% range). The corresponding estimates produced by MAGICC 6.0 are 435⁺¹⁶₋₂₉, 559⁺³⁴₋₄₇, 696⁺⁵²₋₇₅, and 969⁺⁸⁰₋₁₂₄ ppm.

Furthermore, we use five parameters in the two-box temperature module to capture the behavior of several CMIP3 AOGCMs (i.e., CCCMA_CGCM3_1_T47, CNRM_CM3, CSIRO_MK3_0, GFDL_CM2_0, GFDL_CM2_1, GISS_MODEL_E_H, GISS_MODEL_E_R, IAP_FGOALS1_0_G, INMCM3_0, IPSL_CM4, MEDIUM_CMIP3_ECS3, MIROC3_2_HIRES, MIROC3_2_MEDRES, MIUB_ECHO_G, MPI_ECHAM5, MRI_CGCM2_3_2A, NCAR_CCSM3_0, NCAR_PCM1, UKMO_HADCM3, and UKMO_HADGEM1). We adopt the estimates of climate sensitivity and the forcing associated with CO₂ doubling from the emulation results obtained using MAGICC6 (nos. 31–32 in Table S4) and tune the other three

parameters against the GMT projections to 2100 (nos. 33–35 in Table S4). The calibrated temperature results shown in Figure S2 indicate that the results obtained using MAGICC6.0 and SCM4OPT are similar; however, the uncertainty ranges obtained using the latter model are slightly larger. These larger uncertainty ranges are partly propagated from the carbon cycle and result partly from the climate system.

Compared to the DICE model or other optimization IAMs, such as FUND and PAGE, SCM4OPT explicitly considers both mitigation and adaptation climate options with active feedbacks from climate change using the state-of-the-art scenario assumptions and covers a full suite of anthropogenic emissions that are of great importance for assessing low climate targets with stabilization (Su et al. 2017). However, the uncertainty ranges of CO₂ concentrations are larger than the results obtained using MAGICC 6.0, because the treatments of some processes are simplified to enable the complex evolution of the carbon cycle to be incorporated into the optimization procedure used in the IAM, and simplified processes also exist in the climate module. We calibrate the temperature output to be consistent with the results obtained using MAGICC 6.0; thus, the climate change-related uncertainties can be minimized.

Experimental setup

This study uses the SSP2 as a socioeconomic projection for the future. The SSP2 describes a historical development pattern of moderate challenges within both mitigation and adaptation (Fricko et al. 2017). We explore three cases. (1) in BaseC, no climate policy is implemented in the future; (2) in 20DEG, the temperature increase is kept below 2 °C; and (3) in 15DEG, the temperature increase is kept below 1.5 °C. In this analysis, we assume that the temperature targets are met by the end of this century.

We evaluate 200 parameter combinations for each case and calculate the quantiles corresponding to the given probabilities for individual years. We follow the intervals used in the IPCC definition of likelihood (IPCC 2007). Specifically, the (1) median indicates the median of the probability distribution; (2) likely indicates a 66% probability or the percentile range of 17–83%; and (3) extremely likely indicates a 95% probability or the percentile range of 2.5–97.5%. Throughout this paper, the ranges indicated in the text are likely ranges, unless noted otherwise.

Our uncertainty analysis is conducted based on C⁴MIP and CMIP3 to allow comparison with the MAGICC 6.0 results (Meinshausen et al. 2011a, b). A newer model inter-comparison, CMIP5, was released in 2013 (Taylor et al. 2011) for the Fifth Assessment Report (AR5) of the IPCC. It is reported that the mean values and ranges of the GMT changes simulated by the CMIP5 and CMIP3 models are generally consistent [Box TS.6 of IPCC (2013)]. Hence,

using the CMIP5 models would not substantially affect our conclusions.

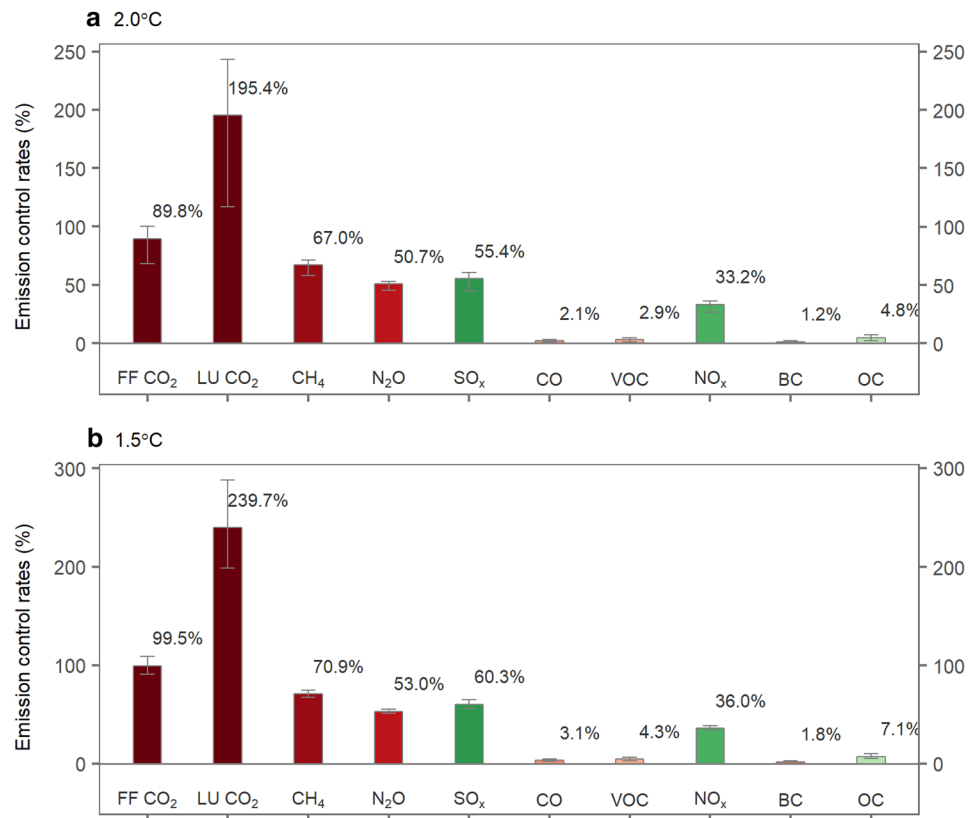
Results and discussion

Emission reductions for 2 and 1.5 °C

We calculate the control rates of individual emissions from each run using the BaseC scenario as a reference and determine the uncertainty ranges for emission reductions with the methods described above. As shown in Fig. 2, the climate-related uncertainties result in wide ranges of reductions in GHGs and aerosols. First, for the 2 °C case, the industrial CO₂ control rate in 2100 is 90⁺¹⁰₋₂₁%, which corresponds to 97⁺¹₋₀% of the total CO₂ reductions, and that for the land-use CO₂ emissions is 195⁺⁴⁸₋₇₈%, which accounts for 3⁻¹₊₀% of the total CO₂ reductions. For the 1.5 °C case, the reduction rate reaches up to 99⁺⁹₋₉% for the industrial CO₂ emissions (accounting for 97⁺⁰₋₀% of the total CO₂ reductions) and 240⁺⁴⁹₋₄₁% for the land-use CO₂ emissions (accounting for 3⁺⁰₋₀% of the total CO₂ reductions). Control rates larger than 100% indicate net negative emissions. Thus, within the likely range, net negative industrial CO₂ emissions are not indicated for the 2 °C case by the end of this century. In contrast, there is an approximately 50% chance that the net CO₂ emissions from industrial sources become negative in the 1.5 °C case. The upper bound (19.4 GtCO₂) and the lower bound (−1.2 GtCO₂) yield a difference of 20.5 GtCO₂ for the total CO₂ emissions in 2100 for the 2 °C target. The corresponding difference for the 1.5 °C target is narrower (i.e., 12.0 GtCO₂; 5.1 GtCO₂; and −6.9 GtCO₂ are the upper and lower bounds). Second, the control rates of CH₄ and N₂O are 67⁺⁴₋₉ and 51⁺²₋₅% for 2 °C and 71⁺⁴₋₄ and 53⁺²₋₂% for 1.5 °C, respectively, because these reductions are assumed to occur mainly from industrial sources, and these abatement potentials are relatively limited under the SSP2 assumptions, compared to reductions in CO₂ emissions. Third, comparatively smaller fractions of SO_x, NO_x, and other aerosols and pollutants are removed because of their small baseline emissions, which are due to the intensive air pollution controls implicit in SSP2 (Fujimori et al. 2017; Rao et al. 2017, Su et al. 2017).

The likely cumulative CO₂ emissions during 2011–2100 are 1665⁺⁶³⁹₋₇₅₂ GtCO₂ for the 2 °C target and 802⁺⁷⁵²₋₅₉₉ GtCO₂ for the 1.5 °C target. These results are larger than previous estimates summarized in the AR5 Synthesis Report (IPCC 2014b; see Table 2.2); the carbon budgets (2011–2100) to achieve 2 and 1.5 °C stabilization with a medium likelihood are 1150–1400 GtCO₂ and 550–600 GtCO₂, respectively. We speculate that the differences come from the fact that our results achieve the temperature targets in 2100 after an overshoot; in contrast, many of the IPCC AR5

Fig. 2 Control rates of anthropogenic emissions in 2100. **a** 2 °C case; **b** 1.5 °C case. The CO₂ emissions include emissions from fossil fuel combustion and industrial processes (FF CO₂) and land use (LU CO₂). The bars indicate the median estimates; the lower and upper bounds of the error bars represent the 17th and 83rd percentiles



scenarios achieve the targets before 2100 and reduce the temperatures further, leading to smaller carbon budgets.

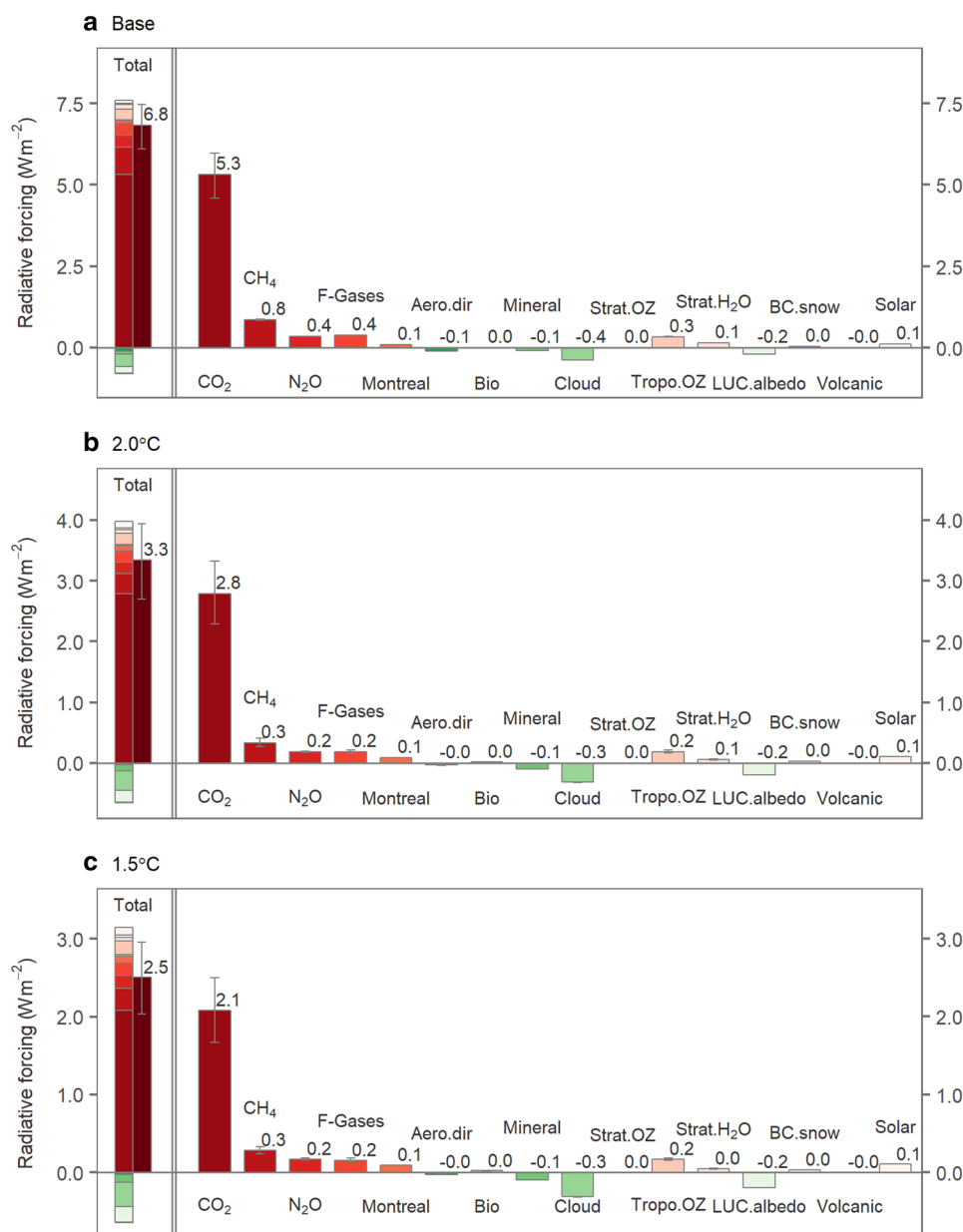
Radiative forcing

Radiative forcing is used to distinguish the causes of perturbations in the climate system. The uncertainty range for each radiative forcing component is shown in Fig. 3. Here, the radiative forcing for the base case is $6.8^{+0.7}_{-0.7}$ Wm⁻² in 2100, leading to a GMT increase of $3.8^{+0.7}_{-0.6}$ °C. This result is consistent with the marker scenario of SSP2 (Fricko et al. 2017). For the 2 °C case, the total forcing in 2100 is $3.3^{+0.6}_{-0.6}$ Wm⁻², and this quantity is $2.5^{+0.4}_{-0.5}$ Wm⁻² for the 1.5 °C case. As for the individual forcing agents, the largest forcing uncertainty comes from CO₂, for which the estimate is $2.8^{+0.5}_{-0.5}$ Wm⁻² in 2100 for the 2 °C case and $2.1^{+0.4}_{-0.4}$ Wm⁻² for the 1.5 °C case. The magnitudes and uncertainty ranges of the other radiative forcing terms are relatively small. Compared to the AR5 transformation pathways, the radiative forcing level for the 2 °C case falls within the category with a range of 430–480 ppm CO₂-eq with an overshoot of <0.4 Wm⁻², whereas the 1.5 °C case is located within the category with a range of 480–530 CO₂-eq ppm with an overshoot of <0.4 Wm⁻² [see Tables 6.2 and 6.3 in IPCC (2014a)].

Economic costs

The carbon prices increase from 90^{+91}_{-38} USD(2005)/tCO₂ in 2040 to 482^{+250}_{-301} USD(2005)/tCO₂ in 2100 for the 2 °C case (Fig. 4a). The median carbon prices for the 1.5 °C case are 1.5 times greater than those for the 2 °C case: 189^{+178}_{-102} USD(2005)/tCO₂ in 2040 and 713^{+301}_{-215} USD(2005)/tCO₂ in 2100. The carbon prices corresponding to the upper ends of the uncertainty ranges are 129–552 USD(2005)/tCO₂ higher than those corresponding to the lower ends for the 2 °C case in the results and 280–516 USD(2005)/tCO₂ for the 1.5 °C case. The average annual mitigation costs in the 1.5 °C case are roughly twice those obtained for the 2 °C case in the same period. Differences can also be identified in the second half of this century, due to the climate-related uncertainties. These differences correspond to 0.5–1.3% of total gross output for the 2 °C case and 1.2–2.0% of total gross output for the 1.5 °C case (Fig. 4b). However, the adaptation costs in 2100 for the 1.5 °C case (0.03% of total gross output) are approximately half those obtained for the 2 °C case (0.05% of total gross output), because stringent climate targets require less adaptation to avoid climate damages (Fig. 4c). The total climate costs resulting from mitigation, adaptation and residual damages (Fig. 4d), which can be expressed as GDP losses, are shown in Fig. 4e. The GDP losses are % and $1.3^{+1.0}_{-0.5}$ in

Fig. 3 Radiative forcing in 2100. **a** Base case; **b** 2 °C case; **c** 1.5 °C case. Total radiative forcing includes anthropogenic forcings (from GHGs and the direct effects of aerosols, including SO_x, NO_x, OC, BC, biomass and mineral dust, cloud cover and albedo, stratospheric ozone, tropospheric ozone, and stratospheric water vapor from CH₄ oxidation) and natural forcings [such as volcanic and solar irradiance changes, which are assumed to be 0.0 and 0.1 Wm⁻² after 2005, respectively (Meinshausen et al. 2011a)]. In the left-hand frame, both the positive and negative forcings are explicitly shown in the bar to the left, and the net forcing obtained by summing all of the forcings is shown by the bar to the right. The right-hand frame shows individual forcing components. The bars indicate the median estimates; the lower and upper bounds of the error bars indicate the 17th and 83rd percentiles



2040 for the 2 °C and 1.5 °C cases and increase to $1.9^{+0.6}_{-0.7}$ and $2.0^{+0.7}_{-0.5}$ in 2100, respectively.

The results indicate that climate-related uncertainties have large impacts on economic assessments of climate change. First, the upper-end carbon prices are approximately quadruple those at the lower ends for both the 2 and 1.5 °C climate targets in the second half of this century. Second, moderate GDP losses occur as a result of achieving the climate targets. However, the upper-end GDP losses are also double those of the lower end for the 2 °C target, whereas the corresponding factor is 3 for the 1.5 °C target in the same period. Third, both the carbon prices and the GDP losses are reduced, and

their ranges become relatively small in 2100 compared to earlier periods, because we assume adaptation options to address climate change. Thus, the total costs of climate change can be reduced eventually, although part of the expense must be devoted to adaptation strategies. Finally, the aggregated costs obtained in this study for the 1.5 °C case are $1.4^{+0.1}_{-0.4}$ times costlier than the 2 °C case. This factor is lower than the factor of 2.2–3.7 reported in Rogelj et al. (2015) for achieving the 1.5 °C-consistent scenario and the medium 2 °C scenario; this difference is likely due to the assumption of moderate future emissions (i.e., the use of the SSP2) and the treatment of adaptation measures. In addition, the GDP losses also show narrower ranges with relatively lower levels compared to the

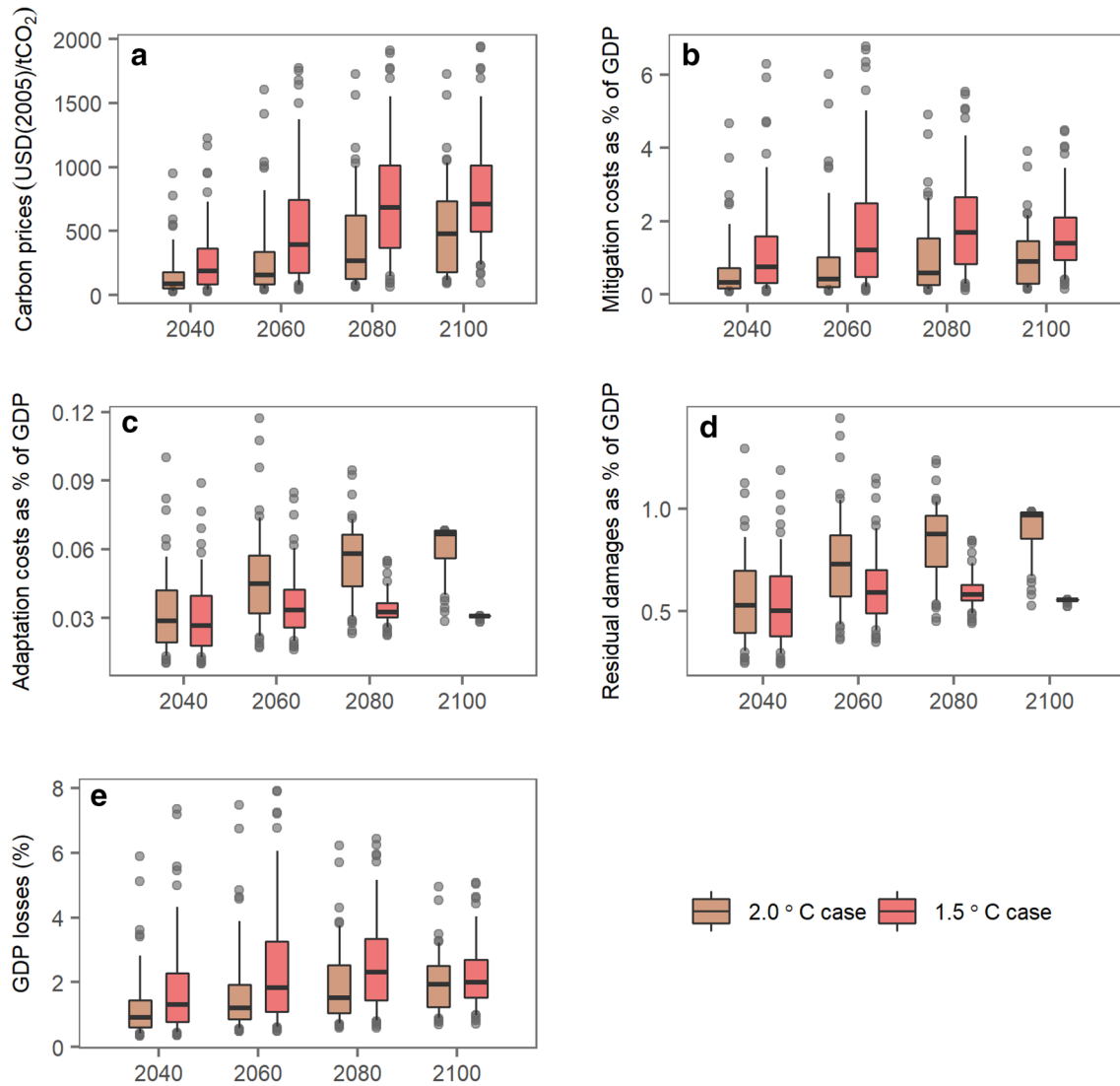


Fig. 4 Economic costs of climate change. **a** Carbon prices. **b** Mitigation costs. **c** Adaptation costs. **d** Residual damages. **e** GDP losses. The adaptation assumptions are based on crude estimates obtained using AD-DICE (de Bruin et al. 2009; de Bruin and Dellink 2011); we re-estimated the parameters using DICE-2013R (Su et al. 2017). The middle horizontal lines are the medians; the ranges between

the lower and upper hinges show the likely probabilities (i.e., the 17th and 83rd percentiles); the ranges between the lower and upper whiskers indicate the extremely likely probabilities (i.e., the 2.5th and 97.5th percentiles); and the points represent outliers beyond the likely ranges

corresponding idealized scenarios implemented for AR5; in Fig. 6.21 in IPCC (2014a), the 430–480 ppm CO₂-eq scenarios are associated with GDP losses of approximately 3–9% in 2100, whereas the 480–530 ppm CO₂-eq scenarios are associated with GDP losses of approximately 4–10% in 2100. Again, the moderate future emissions and the introduction of adaptation may reduce the GDP losses in our study, whereas considering both socioeconomic and climate-related uncertainties may widen the range of uncertainty for the AR5 scenarios.

Conclusions

This study evaluates emission pathways that can be followed to achieve the Paris 2 and 1.5 °C targets by 2100 while considering uncertainties in the carbon cycle and the climate system and explores how such uncertainties influence socioeconomic outcomes. Our results generally illustrate the significance of climate-related uncertainties

in socioeconomic assessments of climate policies. We obtain the following specific findings.

First, the climate-related uncertainties lead to a difference of 20.5 GtCO₂ in the 2100 CO₂ emission levels corresponding to the upper and lower ends of the likely range for the 2 °C target; this difference is 12.0 GtCO₂ for the 1.5 °C target. The total forcing in 2100 is estimated to be 3.3^{+0.6}_{-0.6} Wm⁻² for the 2 °C target and 2.5^{+0.4}_{-0.5} Wm⁻² for the 1.5 °C target.

Second, the climate change costs are significantly affected by the climate-related uncertainties. To achieve the 2 °C target, the carbon price in 2100 is 482⁺²⁵⁰₋₃₀₁ USD(2005)/tCO₂, whereas it is 713⁺³⁰¹₋₂₁₅ USD(2005)/tCO₂ for the 1.5 °C target. The GDP losses in 2100 are estimated to be 1.9^{+0.6}_{-0.7}% of the total gross output for the 2 °C target and 2.0^{+0.7}_{-0.5}% for the 1.5 °C target.

Acknowledgements This study was supported by the Environment Research and Technology Development Fund (S10) of the Ministry of the Environment of Japan. The authors declare that there are no conflicts of interest. We thank Naota Hanasaki for helpful comments that led to improvements in the paper.

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References

- Anthoff D, Rose S, Tol RSJ, Waldhoff S (2011) The time evolution of the social cost of carbon: an application of FUND. Economics discussion paper no. 2011-44. <https://doi.org/10.2139/ssrn.1974112>
- Bodman RW, Rayner PJ, Karoly DJ (2013) Uncertainty in temperature projections reduced using carbon cycle and climate observations. *Nat Clim Change* 3(8):725–729. <https://doi.org/10.1038/nclimate1903>
- Cobb C, Douglas P (1928) A theory of production. *Am Econ Rev* 18(1): 139–165. <http://www.jstor.org/stable/1811556>. Accessed 1 June 2017
- de Bruin KC, Dellink RB (2011) How harmful are restrictions on adapting to climate change? *Glob Environ Change* 21(1): 34–45. <https://doi.org/10.1016/j.gloenvcha.2010.09.008>
- de Bruin KC, Dellink RB, Tol RSJ (2009) AD-DICE: an implementation of adaptation in the DICE model. *Clim Change* 95(1–2):63–81. <https://doi.org/10.1007/s10584-008-9535-5>
- Douglas PH (1976) The Cobb-Douglas production function once again: its history, its testing, and some new empirical values. *J Polit Econ* 84(5):903–915. <https://doi.org/10.1086/260489>
- Fricko O, Havlik P, Rogelj J, Klimont Z, Gusti M, Johnson N, Riahi K (2017) The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. *Glob Environ Change* 42:251–267. <https://doi.org/10.1016/j.gloenvcha.2016.06.004>
- Fujimori S, Kainuma M, Masui T, Hasegawa T, Dai H (2014a) The effectiveness of energy service demand reduction: a scenario analysis of global climate change mitigation. *Energy Policy* 75:379–391. <https://doi.org/10.1016/j.enpol.2014.09.015>
- Fujimori S, Hasegawa T, Masui T, Takahashi K (2014b) Land use representation in a global CGE model for long-term simulation: CET vs. logit functions. *Food Secur* 6(5):685–699. <https://doi.org/10.1007/s12571-014-0375-z>
- Fujimori S, Su X, Liu JY, Hasegawa T, Takahashi K, Masui T, Takimi M (2016) Implication of Paris Agreement in the context of long-term climate mitigation goals. *SpringerPlus* 5(1):1620. <https://doi.org/10.1186/s40064-016-3235-9>
- Fujimori S, Hasegawa T, Masui T, Takahashi K, Herran DS, Dai H, Hijioka Y, Kainuma M (2017) SSP3: AIM implementation of Shared Socioeconomic Pathways. *Glob Environ Change* 42:268–283. <https://doi.org/10.1016/j.gloenvcha.2016.06.009>
- Gillingham K, Nordhaus WD, Anthoff D, Blanford G, Bosetti V, Christensen P, Sztorc P (2015) Modeling uncertainty in climate change: a multi-model comparison (Working Paper Series)
- Heal G, Millner A (2014) Reflections uncertainty and decision making in climate change economics. *Rev Environ Econ Policy* 8(1):120–137. <https://doi.org/10.1093/reep/ret023>
- Hicks JR (1966) The theory of wages, 2nd edn. St. Martin's Press, New York
- Hope C (2011) The social cost of CO₂ from the PAGE09 model. Economics discussion paper no. 2011-39. <https://doi.org/10.2139/ssrn.1973863>
- Hope C (2013) Critical issues for the calculation of the social cost of CO₂: why the estimates from PAGE09 are higher than those from PAGE2002. *Clim Change* 117:531–543. <https://doi.org/10.1007/s10584-012-0633-z>
- IPCC (2007) Historical overview of climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- IPCC (2013) Technical summary. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen K, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York, pp 33–115. <https://doi.org/10.1017/CBO9781107415324.005>
- IPCC (2014a) Assessing transformation pathways. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC (eds) Climate change 2014: mitigation of climate change. Contribution of Working Group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 413–510
- IPCC (2014b) Future climate changes, risks and impacts. In: Pachauri RK, Meyer LA (eds) Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Geneva, pp 55–74
- Masui T, Matsumoto K, Hijioka Y, Kinoshita T, Nozawa T, Ishiwatari S, Kato E, Shukla PR, Yamagata Y, Kainuma M (2011) An emission pathway for stabilization at 6 Wm⁻² radiative forcing. *Clim Change* 109(1–2):59–76. <https://doi.org/10.1007/s10584-011-0150-5>
- Meinshausen M, Raper SCB, Wigley TML (2011a) Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—part 1: model description and calibration. *Atmos Chem Phys* 11(4):1417–1456. <https://doi.org/10.5194/acp-11-1417-2011>

- Meinshausen M, Wigley TML, Raper SCB (2011b) Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—part 2: applications. *Atmos Chem Phys* 11(4):1457–1471. <https://doi.org/10.5194/acp-11-1457-2011>
- Metcalf G, Stock J (2015) The role of integrated assessment models in climate policy: a user's guide and assessment. https://www.belfercenter.org/sites/default/files/legacy/files/dp68_metcalf-stock.pdf. Accessed 1 June 2017
- Nordhaus W (2013) *The climate casino: risk, uncertainty, and economics for a warming world*. Yale University Press, New Haven, London
- Nordhaus W (2014) Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches. *J Assoc Environ Resour Econ* 1(1/2):273–312. <https://doi.org/10.1086/676035>
- Nordhaus W, Sztorc P (2013) DICE 2013R: introduction and user's manual. http://www.econ.yale.edu/~nordhaus/homepage/documents/DICE_Manual_100413r1.pdf. Accessed 1 June 2017
- Ramsey FP (1928) A mathematical theory of saving. *Econ J* 38 (152): 543–559. <https://www.jstor.org/stable/2224098>
- Rao S, Klimont Z, Smith SJ, Dingenen RV, Dentener F, Bouwman L, Tavoni M (2017) Future air pollution in the Shared Socio-economic Pathways. *Glob Environ Change* 42:346–358. <https://doi.org/10.1016/j.gloenvcha.2016.05.012>
- Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, Kindermann G, Nakicenovic N, Rafaj P (2011) RCP 8.5—a scenario of comparatively high greenhouse gas emissions. *Clim Change* 109(1–2):33–57. <https://doi.org/10.1007/s10584-011-0149-y>
- Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V, Riahi K (2015) Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat Clim Change* 5(6):519–527. <https://doi.org/10.1038/nclimate2572>
- Rotmans J, van Asselt MBA (2001) Uncertainty in integrated assessment modelling: a labyrinthine path. *Integr Assess* 2(2):43–55. <https://doi.org/10.1023/A:1011588816469>
- Su X, Takahashi K, Fujimori S, Hasegawa T, Tanaka K, Kato E, Shiogama H, Masui T, Emori S (2017) Emission pathways to achieve 2.0 °C and 1.5 °C climate targets. *Earth's Future* 5:592–604. <https://doi.org/10.1002/2016EF000492>
- Tanaka K, Raddatz T, O'Neill BC, Reick CH (2009) Insufficient forcing uncertainty underestimates the risk of high climate sensitivity. *Geophys Res Lett* 36(16):L16709. <https://doi.org/10.1029/2009gl039642>
- Taylor KE, Stouffer RJ, Meehl GA (2011) An overview of CMIP5 and the experiment design. *Bull Am Meteorol Soc* 93:485–498. <https://doi.org/10.1175/BAMS-D-11-00094.1>
- Thomson A, Calvin K, Smith S, Kyle GP, Volke A, Patel P, Edmonds J (2011) RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Clim Change* 109(1–2):77–94. <https://doi.org/10.1007/s10584-011-0151-4>
- van Asselt MBA, Rotmans J (2002) Uncertainty in integrated assessment modelling. *Clim Change* 54(1):75–105. <https://doi.org/10.1023/A:1015783803445>
- van den Bergh JCJM., Botzen WJW (2014) A lower bound to the social cost of CO₂ emissions. *Nat Clim Change* 4(4):253–258. <https://doi.org/10.1038/nclimate2135>
- van den Bergh JCJM., Botzen WJW (2015) Monetary valuation of the social cost of CO₂ emissions: a critical survey. *Ecol Econ* 114:33–46. <https://doi.org/10.1016/j.ecolecon.2015.03.015>
- Vuuren D, Stehfest E, Elzen MJ, Kram T, Vliet J, Deetman S, Ruijven B (2011) RCP2.6: exploring the possibility to keep global mean temperature increase below 2 °C. *Clim Change* 109(1–2):95–116. <https://doi.org/10.1007/s10584-011-0152-3>
- Weyant J (2017) Some contributions of integrated assessment models of global climate change. *Rev Environ Econ Policy* 11(1):115–137. <https://doi.org/10.1093/reep/rew018>