Report 348
February 2021

Changing the Global Energy System: Temperature Implications of the Different Storylines in the 2021 Shell Energy Transformation Scenarios

Sergey Paltsev, Andrei Sokolov, Martin Haigh, David Hone and Jennifer Morris

MIT Joint Program on the Science and Policy of Global Change combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Joint Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the **Center for Global Change Science (CGCS)** and the **Center for Energy and Environmental Policy Research (CEEPR)**. These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This report is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn,
Joint Program Director

MIT Joint Program on the Science and Policy of Global Change

Massachusetts Institute of Technology
77 Massachusetts Ave., E19-411
Cambridge MA 02139-4307 (USA)

T (617) 253-7492 **F** (617) 253-9845
globalchange@mit.edu
http://globalchange.mit.edu/

GLOBAL CHANGE

FEBRUARY 2021

Changing the Global Energy System: Temperature Implications of the Different Storylines in the 2021 Shell Energy Transformation Scenarios

Sergey Paltsev, Andrei Sokolov, Martin Haigh, David Hone and Jennifer Morris

Abstract: To meet the long-term goals of the Paris Agreement, the global energy system needs to transition to a radically different fuel mix than currently in use. We analyze temperature implications of three scenarios of energy transformation developed by Shell International. The *Islands* and *Waves* scenarios explore the world development without any specific focus on a pre-determined temperature target. The *Islands* scenario envisions the world focused on nationalism and own security in a context of steady technological development, while the *Waves* scenario examines the world that focuses on development first and foremost and only changes late to address climate. The *Sky 1.5* scenario explores the challenge of moving to a global economy with net-zero greenhouse gas (GHG) emissions in the second half of the century (specifically by the year of 2067). Using the MIT Integrated Global System Modeling (IGSM) framework, we simulate 400-member ensembles, reflecting uncertainty in the Earth system response, of global temperature change associated with each scenario by 2100 (mean of 2096–2100) relative to pre-industrial (mean of 1850–1900) levels. We find that for the median climate parameters, the global surface temperature increase is 2.52°C for the *Islands* scenario, 2.28°C for the *Waves* scenario, and 1.47°C for the *Sky 1.5* scenario. The likely (33%-66%) range in 2100 is 2.40–2.64°C for the *Islands* scenario, 2.19–2.43°C for the *Waves* scenario, and 1.40–1.59°C for the *Sky 1.5* scenario.

1. Introduction

Virtually all countries of the world participate in the Paris Agreement (UN, 2015), which has a goal of keeping the increase in the global average surface temperature to "well below" 2°C relative to preindustrial levels, and to pursue efforts to limit the temperature rise to 1.5°C. However, globally coordinated climate policy designed to achieve this goal is still not in place, and the level of pledged mitigation action varies significantly across countries. Still, with growing pressure from society, more and more government and industry actions are moving the world towards decarbonization. A growing number of administrative and business entities have declared "net-zero" emissions targets and other decarbonization actions. Societal pressures and technological trends drive a reinforcing mechanism for action: pressure to pursue low-carbon solutions results in a growing array of low-carbon options, which in turn generates more pressure to employ those options (Morris *et al.*, 2020). These trends drive a transition in the energy system that leads to fewer emissions.

Global greenhouse gas (GHG) emissions are also affected by the Covid-19 pandemic, which has impacted all economic activity, including climate-related actions. While a declining trend for emissions is a good sign for reaching climate goals, negative impacts of the pandemic on economic growth and the ways to stimulate economies provide a complex picture for future decarbonization efforts.

In a slow growth world, emissions are lower due to less consumption, but there are also fewer resources are available for governments to support clean alternatives or for private companies to invest in new technologies. If the markets are not growing, new technologies also have a harder time competing for market share because they need to push out larger fractions of incumbent sources. Further, a prolonged slow growth would keep people in poverty and increase pressure for policies to address otherwise rising levels of inequality.

In a high growth situation, high demand and high energy prices create substantial incentives for new innovations. Growing demand and market share is a way to drive down the costs of new technologies. When demand for energy is growing, new energy sources mostly add to the mix rather than force an early and costly retirement of existing energy sources. However, without proper emission reduction policies, the growth will not be environmentally friendly.

Regardless of the pace of economic development, governments need to intervene to promote the climate sustainability agenda. The amount of resources available for such interventions is highly affected by the Covid-19 crisis. The crisis has also seen many growing negative trends related to protectionism, populism, and nationalism. For a climate problem that requires a global solution, these negative tendencies make global decarbonization pathways an even more challenging undertaking.

However, as the global average surface temperature rises and the impacts become increasingly visible, the need for energy transition will consistently return to the spotlight. This pressure has the potential to drive prolonged and sustained efforts by governments and industries to provide coherent policy support and technological leadership, especially in many sectors where solutions for decarbonization are still under development, which are required to achieve long-term temperature goals. Energy scenarios are important to assess the energy system transition required to mitigate climate challenges and to guide policy makers and industry leaders.

Numerous expert groups and individual researchers produce energy scenarios and assess their implications for climate. The Intergovernmental Panel on Climate Change (IPCC) produces periodic reports that assess the literature relevant to understanding the impacts of climate change. These reports cover scenarios of the future of the energy system, with some scenarios developed by the members of the Integrated Assessment Model Consortium (IAMC). Other well-known scenario producers include the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the U.S. Energy Information Administration (EIA), and energy companies, such as Shell, BP, and ExxonMobil.

The goal of this paper is to provide an assessment of temperature implications of the latest Shell scenarios (Shell, 2021). We apply the outcomes from the Shell World Energy Model profiles for GHG emissions to the MIT Integrated Global System Modeling (IGSM) framework, which links the Economic Projection and Policy Analysis (EPPA) model to the MIT Earth System Model (MESM). EPPA is a recursive-dynamic multi-sector, multi-region computable general equilibrium (CGE) model of the world economy (Chen *et al.*, 2016; Paltsev *et al.*, 2005). It is designed to develop projections of economic growth, energy transitions and anthropogenic emissions of greenhouse gas and air pollutants. MESM is an Earth system model of intermediate complexity, modeling the Earth's physical and biological systems to project environmental conditions that result from human activity, including atmospheric concentrations of greenhouse gases, temperature, precipitation, ice and snow extent, sea level, ocean acidity and temperature, among other outcomes (Sokolov, *et al.*, 2018).

The paper is organized in the following way. In Section 2 we describe GHG emissions in the scenarios that we consider. Section 3 discusses the resulting carbon emissions and uptakes. In Section 4 we report CO_2 and equivalent CO_2 concentrations. Section 5 discusses the temperature implications, including the results from 400-member ensembles that reflect uncertainty in the Earth system response.

2. Anthropogenic GHG Emissions

Long-term energy projections are needed to assess the climate impacts of different scenarios. In this paper, we use the energy system projections for the *Islands*, *Waves*, and *Sky 1.5* scenarios developed by Shell (see Shell (2021) for the details behind each scenario) and implement them in the IGSM model. Here we focus on GHG emissions resulting from the projected long-term changes in the energy system and their implications for the changes in global temperature. The scenarios also include the impact of the Covid-19 pandemic on emissions, which is projected to be only short-term.

The *Islands* scenario assumes that governments and societies decide to focus on their own security, with a new emphasis on nationalism threatening to unravel the post-war geopolitical order. Although the normal course of equipment and infrastructure replacement and the deployment of cleaner technologies bring progress and eventually net-zero emissions, the world overshoots the timeline and does not achieve the goals of the Paris agreement. Instead there is late and slow decarbonization. The resulting GHG emissions for the *Islands* scenario are illustrated in **Figure 1**. Net emissions grow from about 40 gigatonnes of CO_2-equivaent (Gt CO_2e) in 2000 to about 60 Gt CO_2e in 2030, then reduce slightly until 2055, with a much faster reduction afterwards to about 20 Gt CO_2e in 2100.

In the *Waves* scenario, the initial response to the crises of 2020 is to repair the economy – a focus on wealth first. Other underlying societal and environmental pressures receive less attention initially until their relative neglect provokes backlash reactions. Then, moving quickly, but starting later than required to meet the goals of the Paris Agreement, global society achieves an energy system with net-zero emissions. This scenario involves late, but fast, decarbonization. Unlike the *Sky 1.5* scenario, decarbonization in the *Waves* scenario has its primary focus on the elimination of fossil energy. The resulting GHG emissions in the *Waves* scenario are provided in **Figure 2**. In this scenario, net emissions grow even more than in the *Islands* scenario by 2040, to about 64 Gt CO_2e, then GHG emissions in the *Waves* scenario are reduced to about 10 Gt CO_2e in 2100.

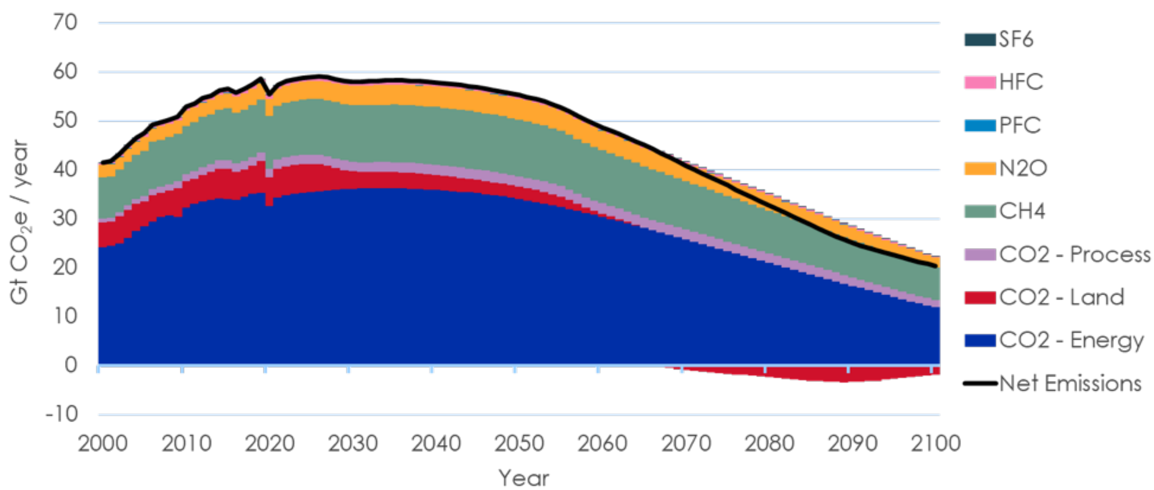

Figure 1. Global GHG Emissions in the *Islands* Scenario

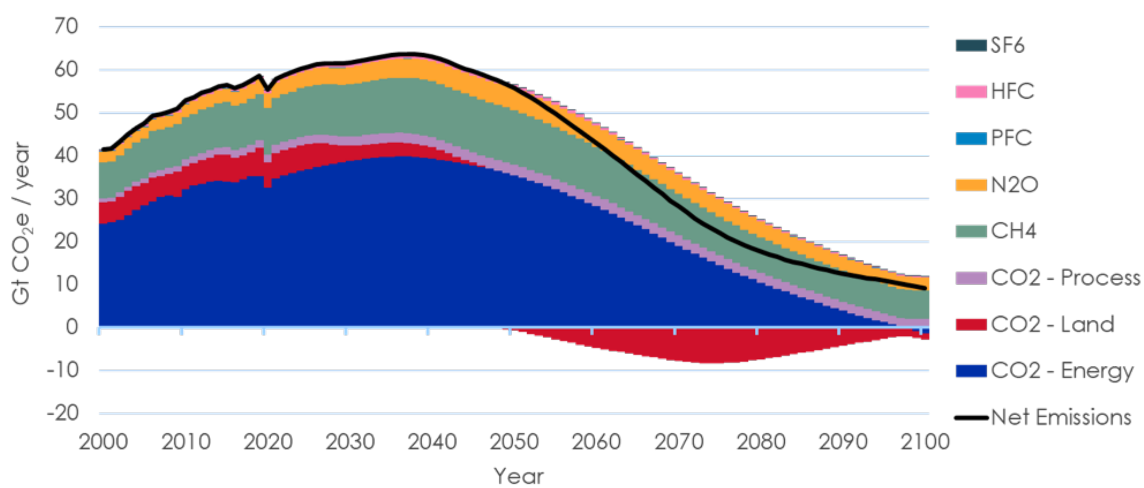

Figure 2. Global GHG Emissions in the *Waves* Scenario

In the *Sky 1.5* scenario, the initial response to the crises of 2020 is to focus on responding to the pandemic and related challenges to public wellbeing – a focus on health first. Lessons learned from shared best practices, alignments of diverse interests and institutional improvements help create a pathway to health not only of people and society, but also of the environment, including meeting the stretch goal of the Paris Agreement. This is a scenario of accelerated decarbonization now. The resulting GHG emissions for the *Sky 1.5* scenario are provided in **Figure 3**. Net emissions peak at about 59 Gt CO_2e in 2024, then they decline to zero in 2067, and stay slightly below zero until 2100.

The *Waves* and *Islands* scenarios are traditional scenarios in that they explore future possible worlds without any specific focus on creating a desired outcome. The *Sky 1.5* scenario also explores a future possible world, but one that designed to achieve a certain outcome. It is aspirational as well as being rooted in today's realities. In the spirit of the original *Sky* scenario published in 2018 (Shell, 2018), the revised *Sky 1.5* scenario maps the difficult pathway society would need to take to meet the stretched climate goal of the Paris Agreement to limit global average warming to 1.5°C in 2100.

Appendix A compares the trajectories for energy-related CO_2, industrial process CO_2, land-use change CO_2, non-CO_2 GHG gases (CH_4, N_2O, PFC, HFC, SF_6), and SO_2 and in these scenarios. In addition to having very different energy system CO_2 profiles, the three scenarios also see differences in other sources of GHG emissions and aerosols. The *Sky 1.5* scenario manages CO_2 from all sources most comprehensively, with industrial CO_2 reduced by some 75% both through process changes and the application of carbon capture and storage (CCS), building on the basis of a large-scale CCS infrastructure for energy-related CO_2. The *Islands* scenario also sees some CCS applied in processes such as cement manufacture, but in the *Waves* scenario this technology lacks support and never develops commercially and global CO_2 industrial process emissions in this scenario are not reduced below the current levels even by the end of the century. The scenarios envisage a peak in cement production (after the surges caused by large-scale infrastructure builds mature in emerging economies), and further downward pressure in process emissions arises from lower lime production as a result of increased utilization of scrap in steel production. The *Islands* scenario uses a lower cement growth pathway in order to use more wood in construction.

All three scenarios address land use CO_2, with the *Sky 1.5* scenario giving rise to widespread forestry and land management efforts with the land sink increasing to about 13 Gt CO_2 by 2060 and reducing afterwards to about 4 Gt CO_2 by 2100. Land-use CO_2 emissions have proven difficult to eliminate. All scenarios foresee this changing, but over varying timescales. Land-use emissions reach net-zero in 2040 in the *Sky 1.5* scenario, in 2048 in the *Waves* scenario, and in 2066 in the *Islands* scenario. Both the *Islands* and *Waves* scenarios deliver considerable change in the second half of the century and both see an end to deforestation on a global net basis followed by net forest cover increase.

Methane (CH_4) emissions fall in all three scenarios, with fossil methane falling with the decline in fossil fuel use. In addition, the fossil fuel industry also responds to pressure on emissions and implements much improved methane management practices, with the *Sky 1.5* scenario seeing this adopted most comprehensively in the nearer term. Agricultural practices also improve methane emissions, but cannot bring them down significantly. By the end of the century, methane emissions are lowest in the *Sky 1.5* scenario, but still around half peak levels.

Nitrous oxide (N_2O) emissions follow a similar path to methane, partly linked to overall fossil fuel use, but the majority of nitrous oxide emissions continue to come from agricultural soil management. By the end of the century, the *Sky 1.5* scenario sees the most progress through changes in

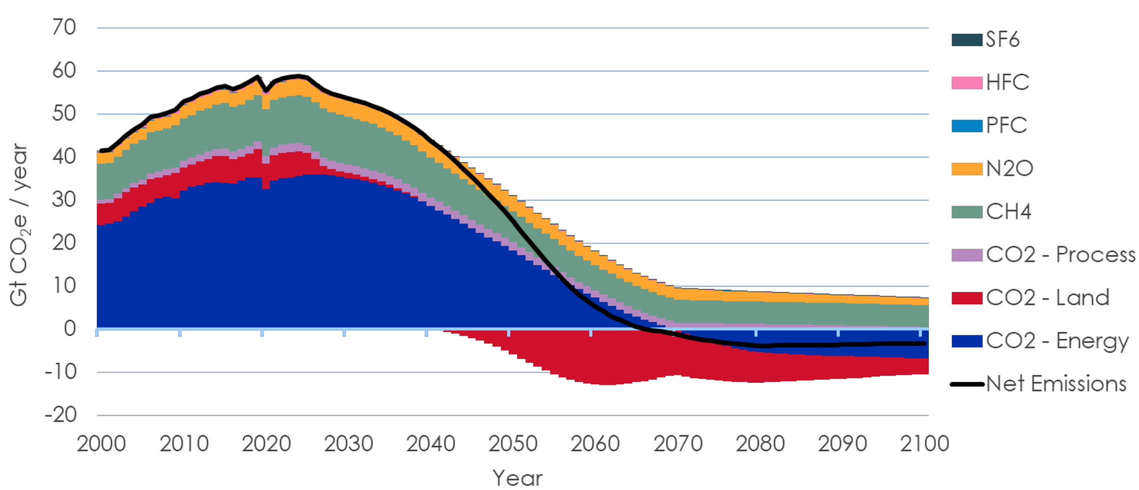

Figure 3. Global GHG Emissions in the *Sky 1.5* Scenario

agriculture and rapid sharing of best practices, including lowering fertilizer use. Agriculture is also addressed more comprehensively in the *Islands* than in the *Waves* scenario due to a strong focus on local problem solving.

In all three scenarios industrial gases are managed, but to differing extents. The *Sky 1.5* scenario projects rapid reductions in PFCs, HFCs and SF_6 as comprehensive actions are taken globally and alternative technologies are aggressively deployed. But in the *Islands* and *Waves* scenarios the transition is slower and more aligned with technology development over time as industrial concerns seek out better performing products and respond to pressure from stakeholders. However, reductions in HFC gases benefit in all three scenarios from the Kigali Amendment to the Montreal Protocol. In all scenarios for all industrial gases, emissions are down by 40% or more by 2100, with emissions in the *Sky 1.5* scenario down by about 90% relative to the current levels.

Sulphur dioxide (SO_2) emissions continuously decline in all three scenarios as the energy transition proceeds: renewable energy backs out fossil fuels in the power generation system, and scrubbing is employed extensively where sulphur remains in fuels. In all three scenarios there is good progress by mid-century with emissions down about 50%, but the transition for metal smelting, another large source of sulphur emissions, takes longer. The *Sky 1.5* scenario is lowest for SO_2 in 2100 with reduction in excess of 80% relative to the current levels.

3. Carbon Emissions and Uptake

Climate simulations with IGSM are carried out in two stages: historical simulations from 1861 to 2005 and forward climate simulations from 2006 to 2100. During the first stage, IGSM is run in a concentration-driven mode forced by observed changes in natural and anthropogenic forcing. In the second stage, IGSM is run in an emissions-driven mode and forced by anthropogenic GHG emissions from the *Islands*, *Waves*, and *Sky 1.5* scenarios. Due to the large share of CO_2 in total emissions and because CO_2 stays in the atmosphere for a very long time, changes in radiative forcing and surface temperature are, to a large extent, defined by changes in CO_2 concentrations. Atmospheric CO_2 concentrations, in their turn, depend on the balance between anthropogenic carbon emissions and carbon uptake by the ocean and terrestrial ecosystems.

Figure 4 shows the total anthropogenic carbon emissions and uptakes for the duration of the simulations. CO_2 concentrations simulated in the second stage of the simulations are defined not only by CO_2 emissions, but also by industrial emissions of CH_4 and CO (that produce CO_2 with ~month to ~decade time delay). For this reason, the implied carbon emissions are shown in Figure 4. Emissions and total uptake peak at about 11.5–12.5 GtC/year and 5.5–6 GtC/year, respectively. There is a noticeable difference between changes

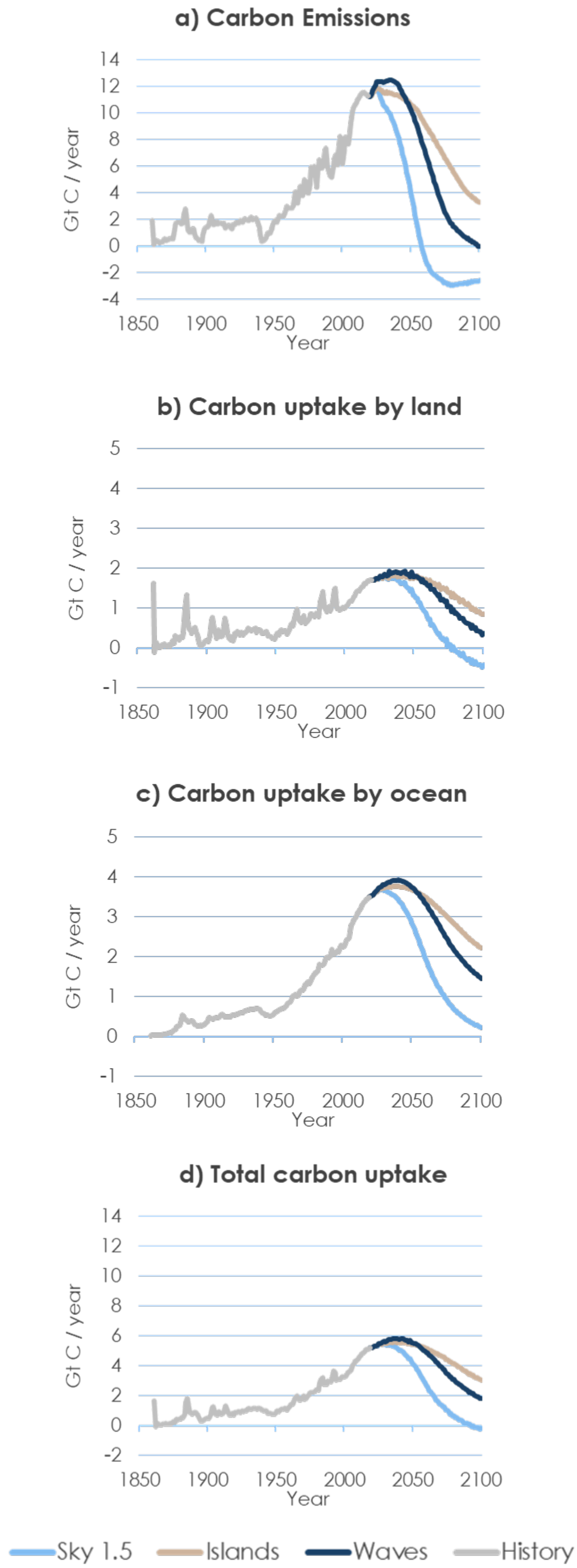

Figure 4. Carbon balance (in Gt C/year): Total net anthropogenic carbon emissions (a), land carbon uptake (b), ocean carbon uptake (c), total (land and ocean) carbon uptake (d)

in emissions and uptake. Emissions peak at about 11.5–12.5 GtC/year while ensemble mean total uptakes peak at about 5.5–6 GtC/year (maximum values of total carbon uptake range from about 2 to 8 GtC/year in the individual runs). As a result, on average about 56–57% of carbon, emitted between 2006 and the time when emissions start to decrease, remains in the atmosphere, meaning that both ocean and terrestrial ecosystems are not in equilibrium with the atmospheric CO_2 level. Therefore, both ocean and land continue to take up carbon after emissions start to decrease. Total carbon uptake remains positive in the *Islands* and *Waves* simulations through 2100 and become negative in the last decade for the *Sky 1.5* scenario. Carbon uptake by the ocean stays positive under all scenarios due to mixing of carbon into deep ocean. In contrast, the terrestrial ecosystem in the *Sky 1.5* scenario becomes carbon source at about 2080.

In **Figure 5** we re-arrange the data from Figure 4 and show the carbon fluxes of total anthropogenic carbon emissions

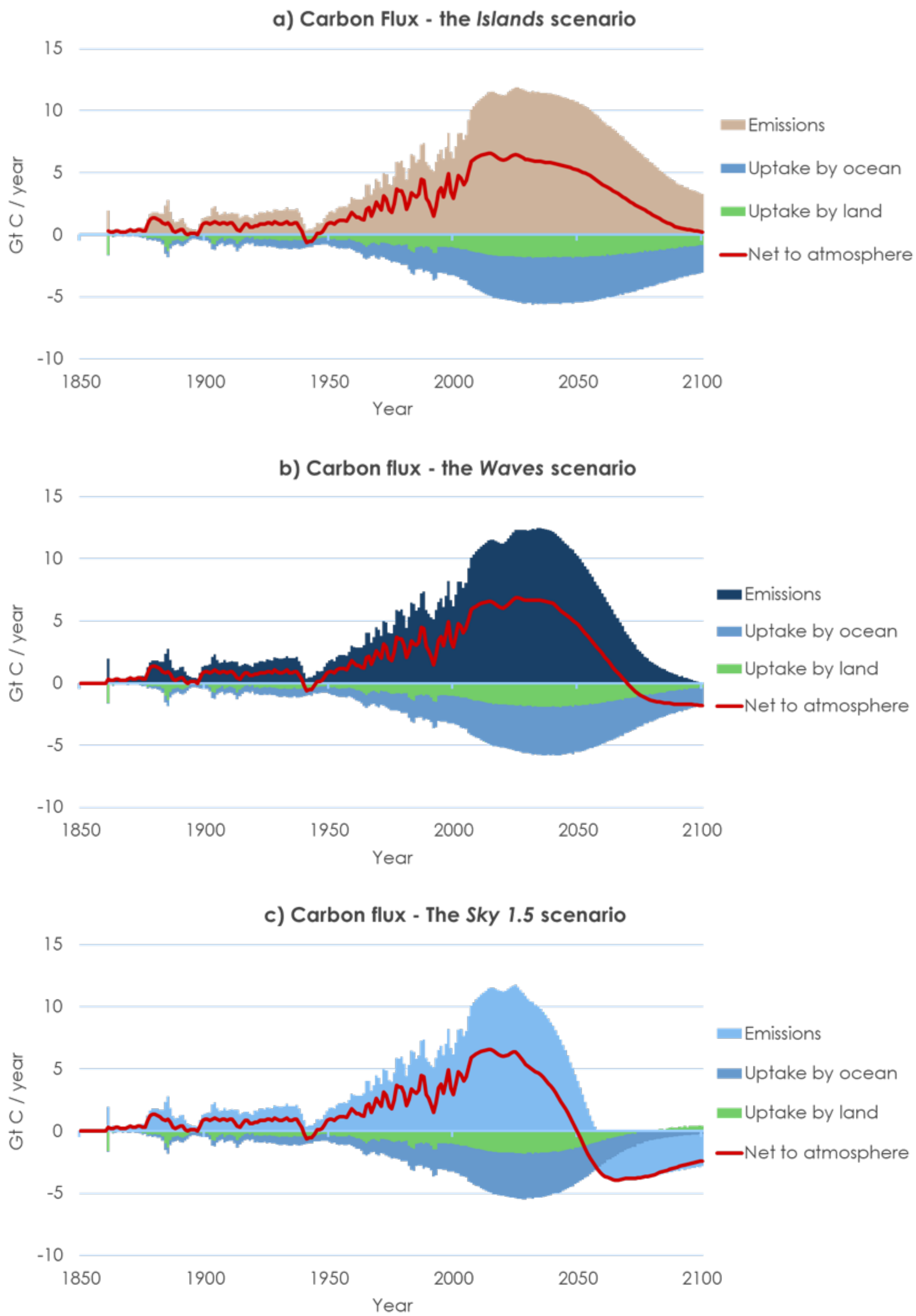

Figure 5. Carbon flux (in Gt C/year) for the *Islands* scenario (panel a), the *Waves* scenario (panel b), the *Sky 1.5* scenario (panel c)

and uptakes for the individual scenarios. By the end of the century, net carbon to the atmosphere approaches zero in the *Islands* scenario and becomes negative in the *Waves* and *Sky 1.5* scenarios.

4. CO_2 and Equivalent CO_2 Concentrations

Changes in CO_2 concentrations (see **Figure 6**) are determined by net emissions (emissions minus total carbon uptake), which remain positive through 2100 in the *Islands* scenario, but become negative in 2070 and 2050 in the *Waves* and *Sky 1.5* scenarios, respectively. From the current CO_2 concentration of about 400 ppm, in the *Islands* scenario CO_2 concentrations increase to about 560 ppm in 2100. In the *Waves* scenario, they rise to about 535 ppm by 2070 and then decrease to about 515 ppm in 2100. In the *Sky 1.5* scenario, CO_2 concentrations increase to about 480 ppm by 2050 and then decrease to about 405 ppm in 2100

The CO_2-equivalent concentrations, shown in **Figure 7**, are calculated from the total radiative forcing relative to 1860. The CO_2-equivalent concentrations shown here account for radiative forcing by all GHGs and aerosols (sulfates, black carbon). It should be noted that there is no direct connection between CO_2 equivalent emissions (that use the global warming potential, GWP, approximation) shown in Figures 1–3, and the CO_2 equivalent concentrations shown in Figure 6 (see Pierrehumbert (2014) for more details). The use of CO_2-equivalent concentrations simply provides another way to compare CO_2 and non-CO_2 radiative forcing.

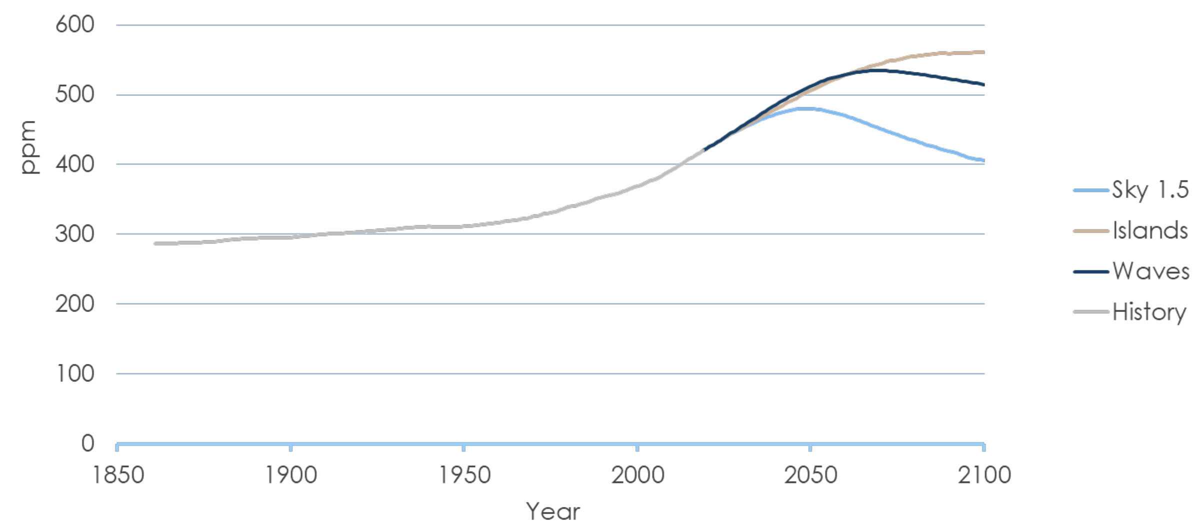

Figure 6. Atmospheric CO_2 concentrations (mole fractions in ppm CO_2)

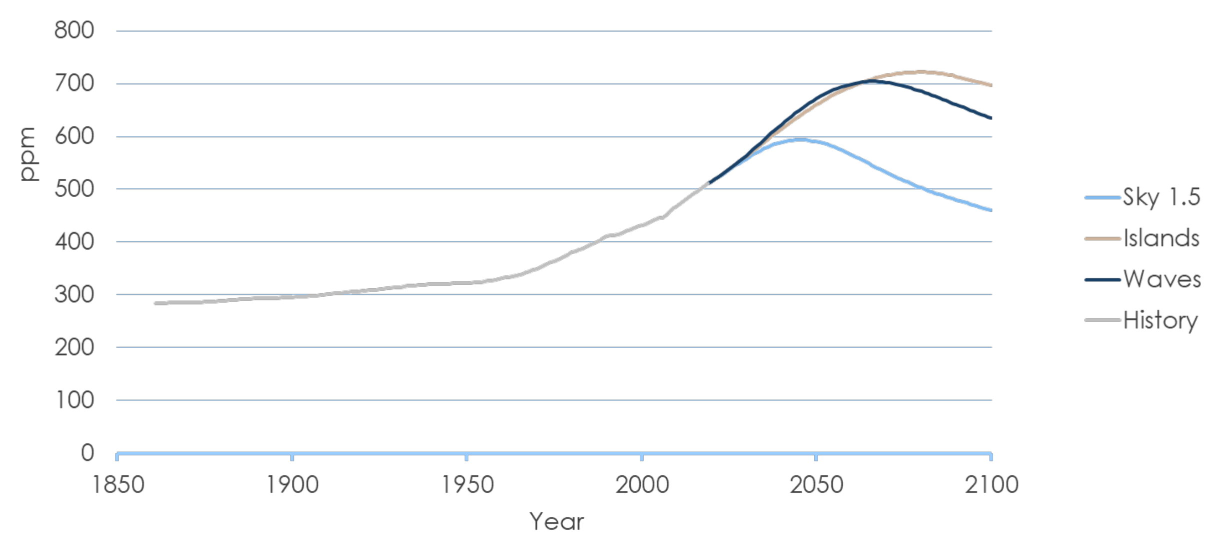

Figure 7. Atmospheric CO_2-equivalent concentrations (mole fractions in ppm CO_2-eq) computed from radiative forcing by all GHGs and aerosols

In all scenarios, the CO_2 -equivalent concentrations rise from the current level of about 480 ppm. In the *Islands* scenario, they increase to about 720 ppm in 2080 and then decrease to about 700 ppm in 2100. In the *Waves* scenario, they rise to about 700 ppm by 2070 and then decrease to about 640 ppm in 2100. In the *Sky 1.5* scenario, CO_2-equivalent concentrations increase to about 600 ppm by 2050 and then decrease to about 460 ppm in 2100.

5. Temperature Implications

The IGSM model calculates changes in the global annual mean surface air temperature relative to a mean of 1861–1880. For the purposes of consistency with the latest IPCC reporting, we converted the results to be relative to a mean of 1850–1900. The results for temperature changes are presented in **Figure 8**, which also shows the observed historic temperature increase and the IGSM model realization for the historic period. For the median values of the model's climate parameters (including a climate sensitivity of 3.2, square root of diffusion coefficient of ocean heat mixing of 1.8 $cm/s^{1/2}$, and radiative forcing due to aerosol radiation interaction of -0.24 W/m^2, see Sokolov *et al* (2018) for details), the *Islands* scenario leads to an increase in the global average surface air temperature of 2.52°C above the preindustrial level by 2100 (measured as a mean of 2096–2100 relative to a mean of 1850–1900). The corresponding increase for the *Waves* scenario is 2.28°C, and for the *Sky 1.5* scenario is 1.47°C.

We also can estimate the year when the indicative threshold of 1.5°C will be exceeded. Using the 5-year centered mean, the global annual mean surface air temperature increase will be higher than 1.5°C in the year 2034 for the *Islands* scenario, in the year 2032 in the *Waves* scenario, and in the year 2036 in the *Sky 1.5* scenario (but *Sky 1.5* returns back below 1.5°C in 2092).

Figures 9–11 show the results for the global temperature change for 400 runs of the *Islands*, *Waves* and *Sky 1.5* scenarios, each run with different values of climate parameters. The 400 samples are chosen from a probability distribution of climate parameters as described in Sokolov *et al.* (2017, 2018). The 90% probability ranges (5%-95%) for the temperate change in a mean of 2096–2100 relative to a mean of 1850–1900 are as follows: 2.01–3.07°C for the *Islands* scenario, 1.84–2.8°C for the *Waves* scenario, and 1.2–1.84°C for the *Sky 1.5* scenario. The 33% probability ranges (33%-66%) are as follows: 2.40–2.64°C for the *Islands* scenario, 2.19–2.43°C for the *Waves* scenario, and 1.40–1.59°C for the *Sky 1.5* scenario. The temperature results for all 400-run ensembles of these scenarios are provided in Appendix B. The carbon uptake results for all 400-run ensembles are provided in Appendix C.

Another way of illustrating the likelihood of reaching various temperature increases relative to preindustrial levels is provided in **Figure 12**, which shows the cumulative probability density. As seen in the figure, the *Sky 1.5* scenario has an 50% probability of remaining below 1.5°C and 90% probability of remaining below 2°C in the last five years of the 21st century relative to the 1850–1900 mean. The probabilities of staying below 2°C are substantially lower for the *Islands* and *Waves* scenarios. They are 14% and 26%, correspondingly. The probabilities of staying below 3°C are 87% for the *Islands* scenario and 95% for the *Waves* scenario.

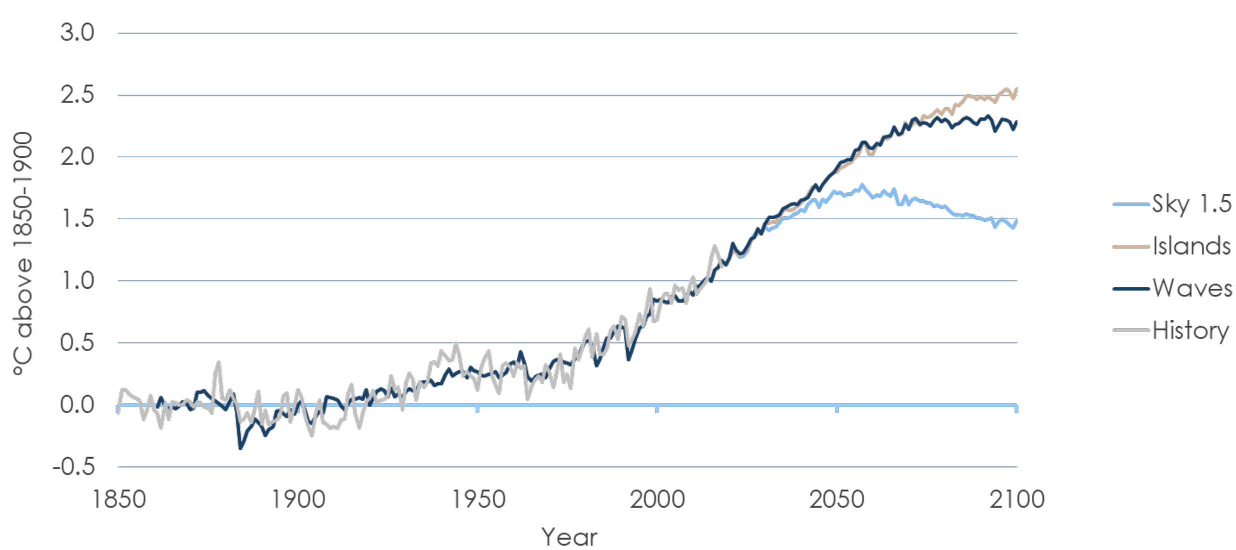

Figure 8. Global average surface air temperature change relative to the preindustrial level of 1850-1990 (°C).

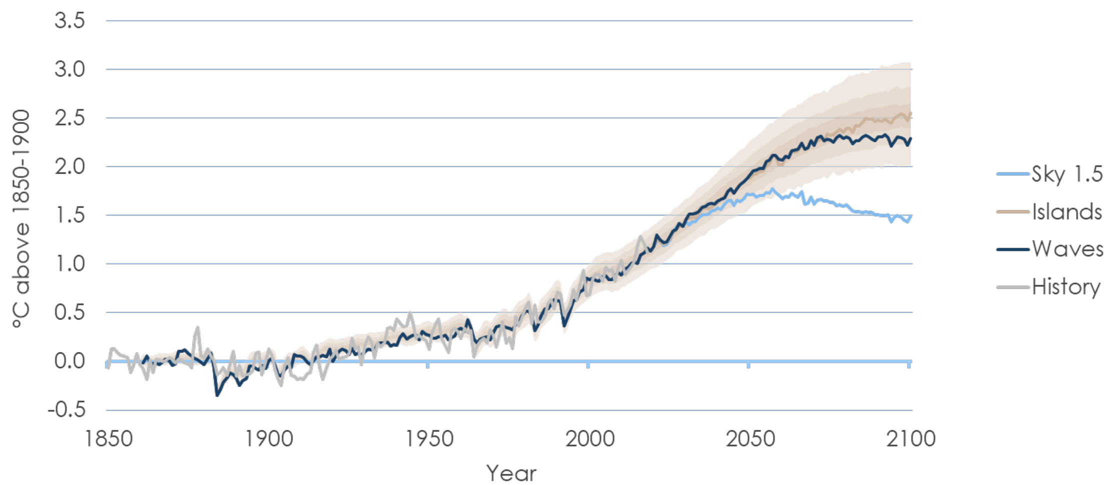

Figure 9. 400-run ensemble results for the *Islands* scenario for global average surface air temperature change relative to the preindustrial level of 1850–1990 (C°). Darker shaded area represents 33-66% probability bound, medium shaded area represents 17-83% probability bound, and lighter shaded area represents 5-95% probability bound.

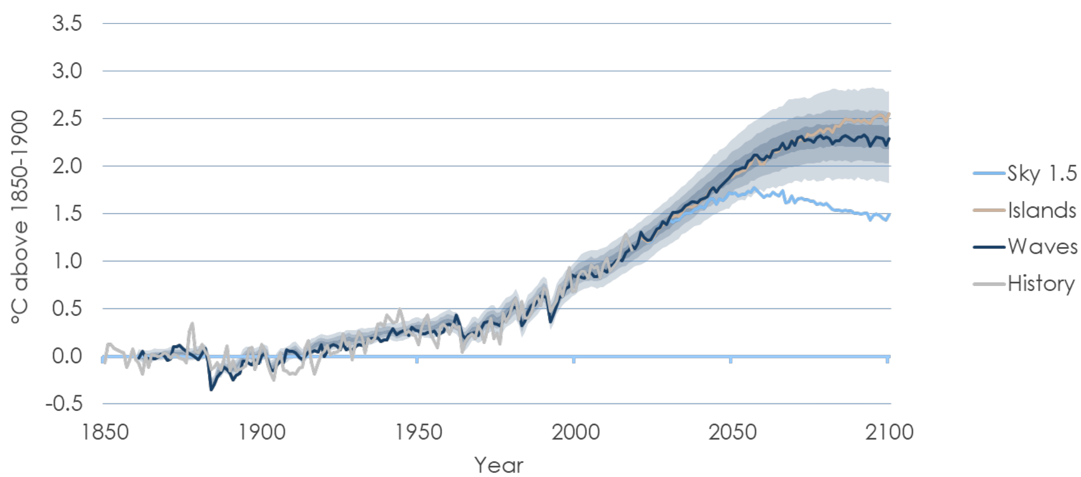

Figure 10. 400-run ensemble results for the *Waves* scenario for global average surface air temperature change relative to the preindustrial level of 1850–1900 (C°). Darker shaded area represents 33-66% probability bound, medium shaded area represents 17-83% probability bound, and lighter shaded area represents 5-95% probability bound.

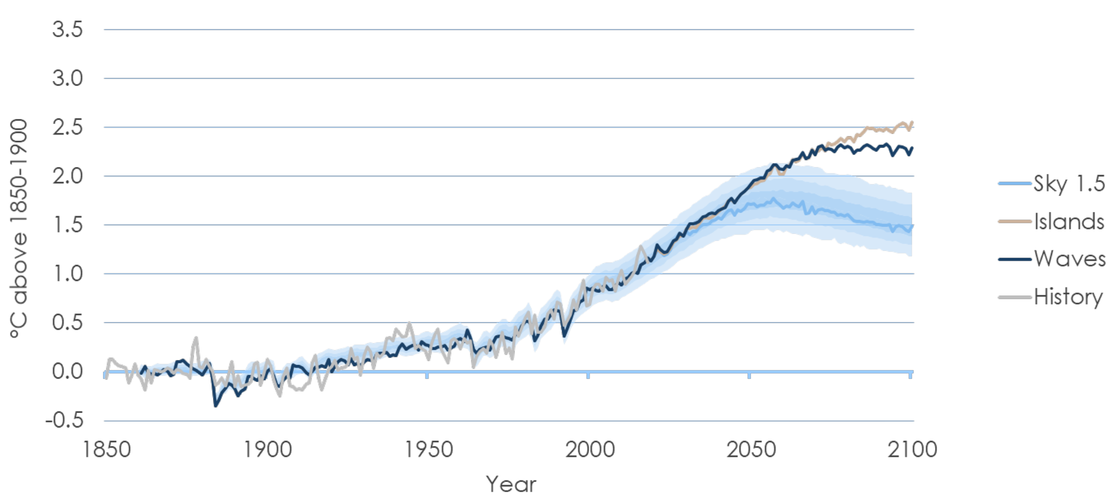

Figure 11. 400-run ensemble results for the *Sky 1.5* scenario for global average surface air temperature change relative to the preindustrial level of 1850–1990 (C°). Darker shaded area represents 33-66% probability bound, medium shaded area represents 17-83% probability bound, and lighter shaded area represents 5-95% probability bound.

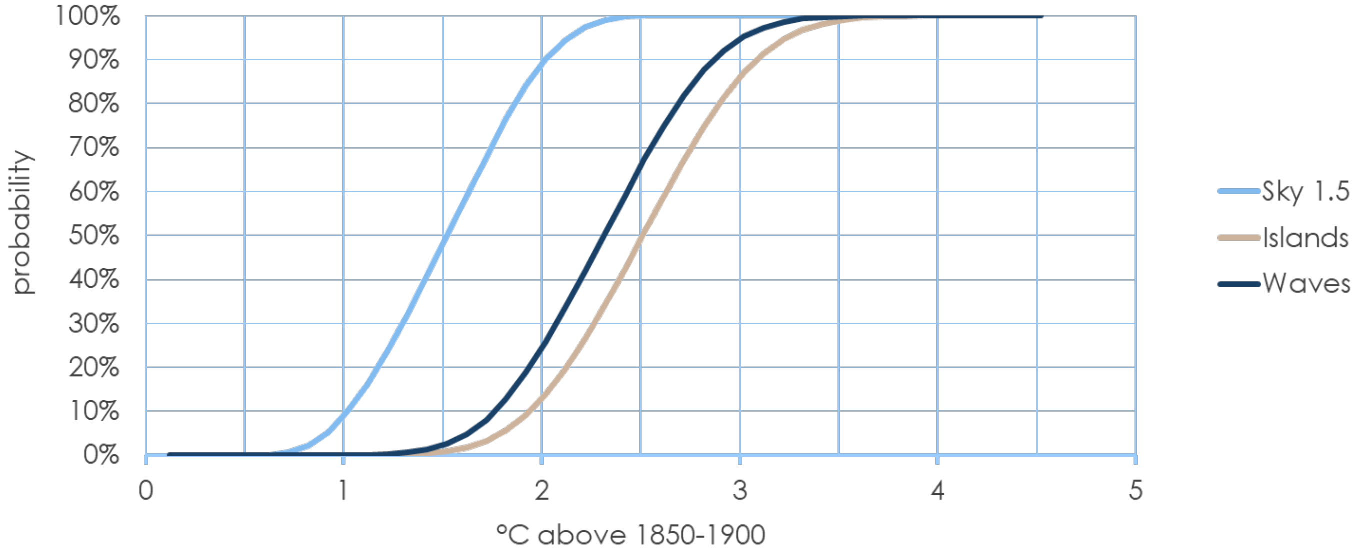

Figure 12. Probability (%) that surface air temperature in the last five years of the 21st century remains below given values (relative to 1850-1900 mean)

6. Conclusions

Meeting the long-term goals of the Paris Agreement requires a dramatic transition in the global energy system. As such, long-term energy, emissions and climate projections are particularly important to assess consistency with the Paris goals and to guide policy makers and industry leaders. Currently, global emissions are affected by the Covid-19 pandemic, which has impacted all economic activity, including climate-related actions. However, the Covid-19 pandemic is projected to have a short-term direct impact on greenhouse gas emissions. The longer-term effect will be most pronounced if it acts as a catalyst for change in the energy transition. Ultimately, government policies and industrial technological leadership is needed for aggressive GHG mitigation.

In this paper, we have analyzed emissions and temperature implications of three scenarios of energy transition developed by Shell International. Using the MIT Integrated Global System Modeling (IGSM) framework, we simulate 400-member ensembles, reflecting uncertainty in the Earth system response of global temperature change associated with the *Islands*, *Waves*, and *Sky 1.5* scenarios by 2100. We find that, for the median climate parameters, the global air surface temperature increase above the pre-industrial levels by 2100 is 2.52°C for the *Islands* scenario, 2.28°C for the *Waves* scenario, and 1.47°C for the *Sky 1.5* scenario. The likely (33%-66%) range in 2100 for the *Islands* scenario is 2.40–2.64°C, for the *Waves* scenario is 2.19–2.43°C, and the *Sky 1.5* scenario is 1.40–1.59°C. By presenting different potential energy futures and their resulting impacts on emissions and temperature, these scenarios can help inform government and industry decisions.

Acknowledgement

The authors gratefully acknowledge Adam Eales and Jamie Bartholomay for their valuable inputs. Shell provided financial support to the MIT Joint Program, to defray costs related to this research. Development of the IGSM framework used in the analysis is supported by an international consortium of government, industry and foundation sponsors of the MIT Joint Program on the Science and Policy of Global Change. For a complete list, see: https://globalchange.mit.edu/sponsors/current. Shell participated actively in this study, supplying the background data behind their scenarios. MIT remains responsible for all analysis and conclusions.

7. References

Chen, H., S. Paltsev, J. Reilly, J. Morris and M. Babiker (2016). Long-term economic modeling for climate change assessment. *Economic Modeling*, 52, 867–883.

Morris, J., D. Hone, M. Haigh, A. Sokolov and S. Paltsev (2020). *Future energy: In search of a scenario reflecting current and future pressures and trends*. Joint Program Report Series **Report 344** (http://globalchange.mit.edu/publication/17501)

Paltsev, S., J. Reilly, H. Jacoby, R. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, M. Babiker (2005). *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4*. Joint Program Report Series **Report 125** (https://globalchange.mit.edu/publication/14578)

Paltsev, S., A. Sokolov, X. Gao and M. Haigh (2018). *Meeting the Goals of the Paris Agreement: Temperature Implications of the Shell Sky Scenario.* Joint Program Report Series **Report 330** (http://globalchange.mit.edu/publication/16995)

Pierrehumbert, R. (2014). Short-lived climate pollution. *Annual Review of Earth and Planetary Sciences*, 42(1): 341.

Shell (2018). *Shell Scenarios: Sky – Meeting the Goals of the Paris Agreement* (http://www.shell.com/skyscenario).

Shell (2021). *The Energy Transformation Scenarios* (https://www.shell.com/transformationscenarios).

Sokolov, A., S. Paltsev, H. Chen, M. Haigh, R. Prinn and E. Monier (2017). *Climate Stabilization at 2°C and Net Zero Carbon Emissions.* Joint Program Report Series **Report 309** (http://globalchange.mit.edu/publication/16629)

Sokolov, A., D. Kicklighter, C.A. Schlosser, C. Wang, E. Monier, B. Brown-Steiner, R. Prinn, C. Forest, X. Gao, A. Libardoni and S. Eastham (2018). Description and Evaluation of the MIT Earth System Model (MESM). *Journal of Advances in Modeling Earth Systems*, 10(8): 1759–1789 (doi: 10.1029/2018MS001277)

UN [United Nations] (2015). *The Paris Agreement*.

Appendix A. GHG emission profiles

Appendix A provides a comparison of trajectories for emissions for individual GHG gases and SO_2 in the *Islands*, *Waves*, and *Sky 1.5* scenarios.

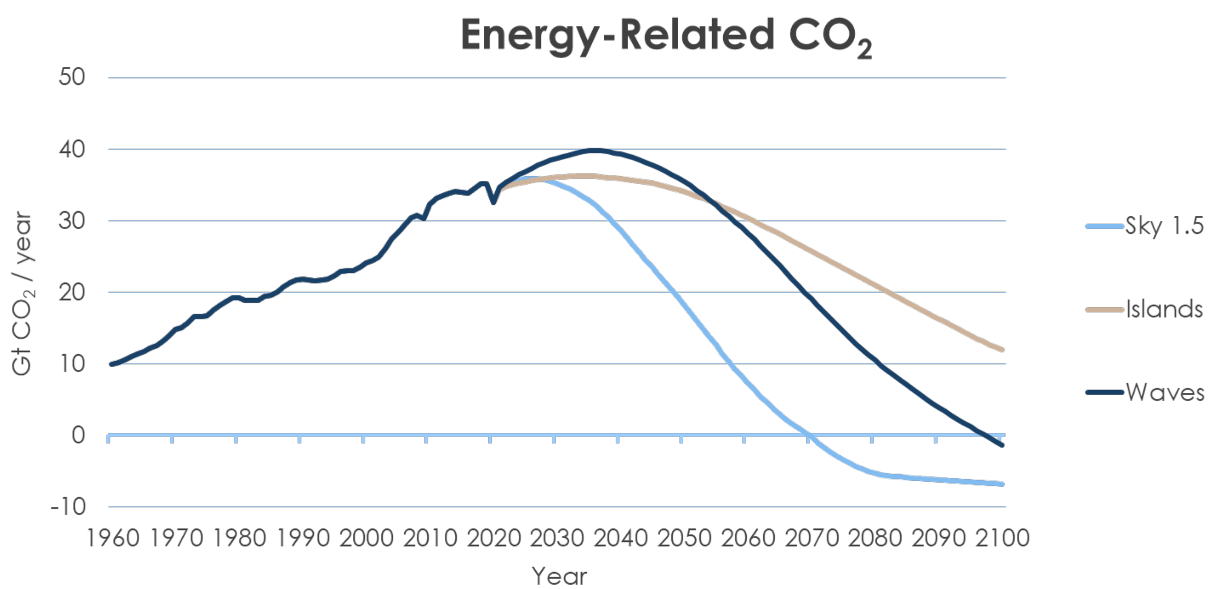

Figure A.1. Energy-related CO_2 emissions

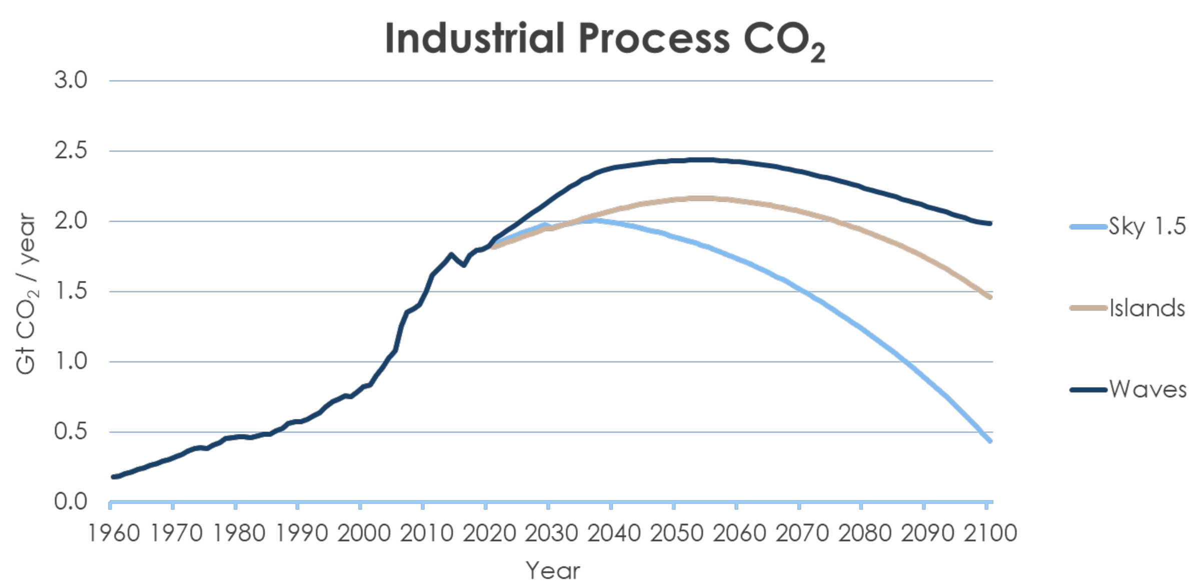

Figure A.2. Industrial CO_2 emissions

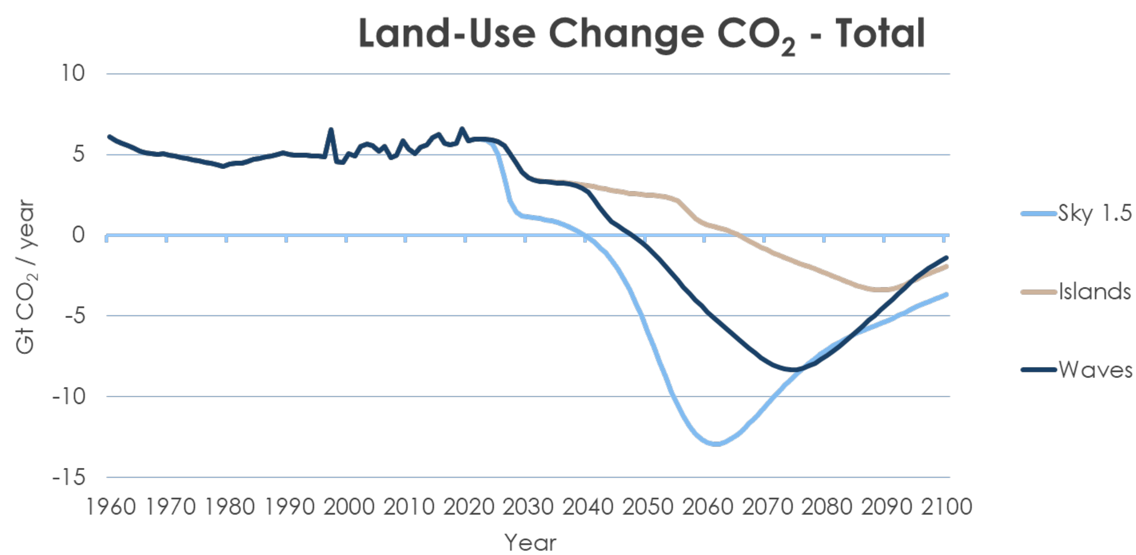

Figure A.3. Land-use change CO_2 emissions

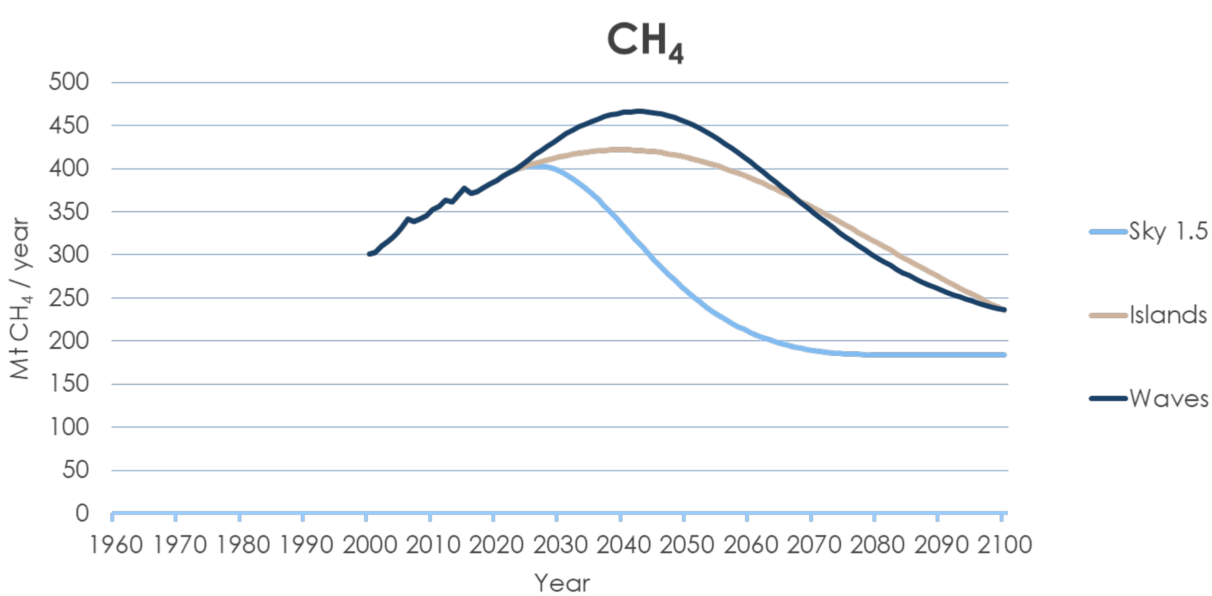

Figure A.4. CH_4 emissions

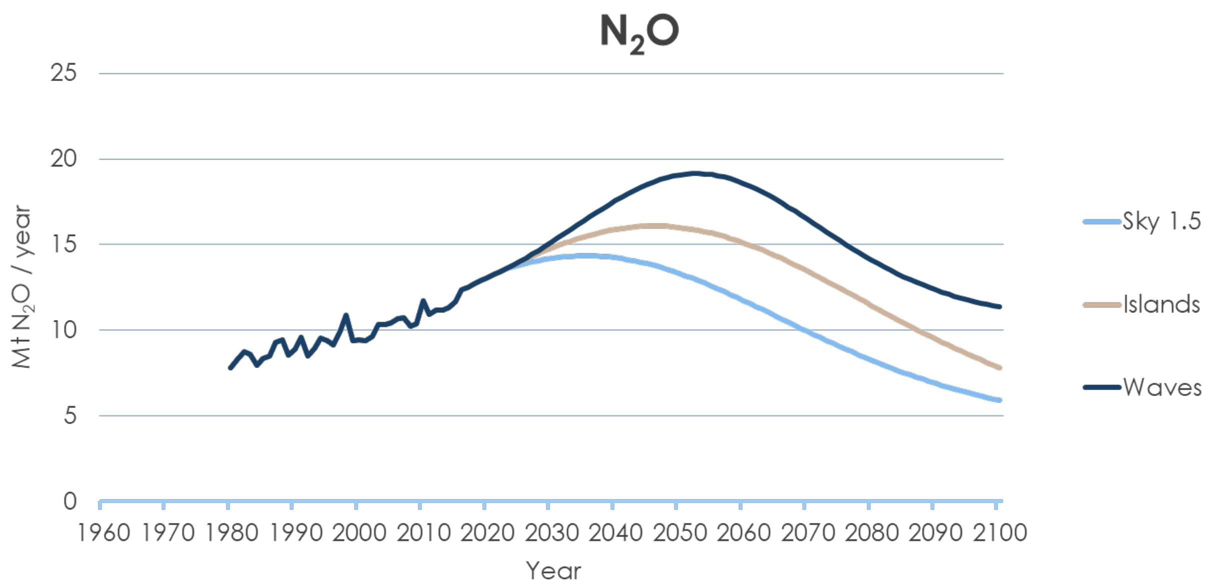

Figure A.5. N_2O emissions

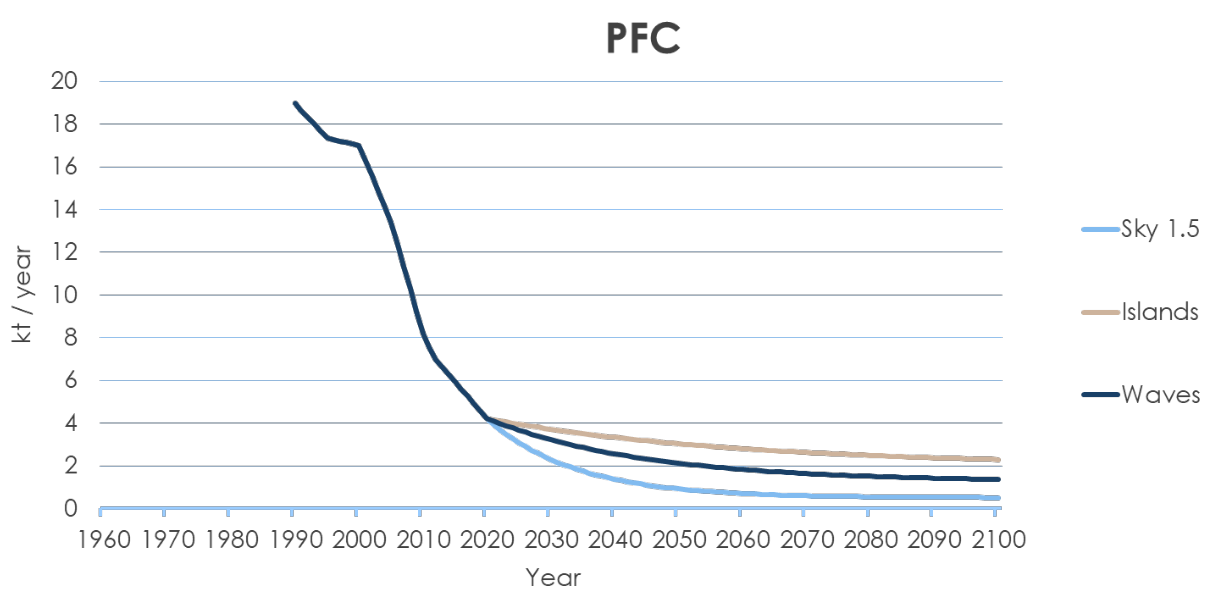

Figure A.6. PFC emissions

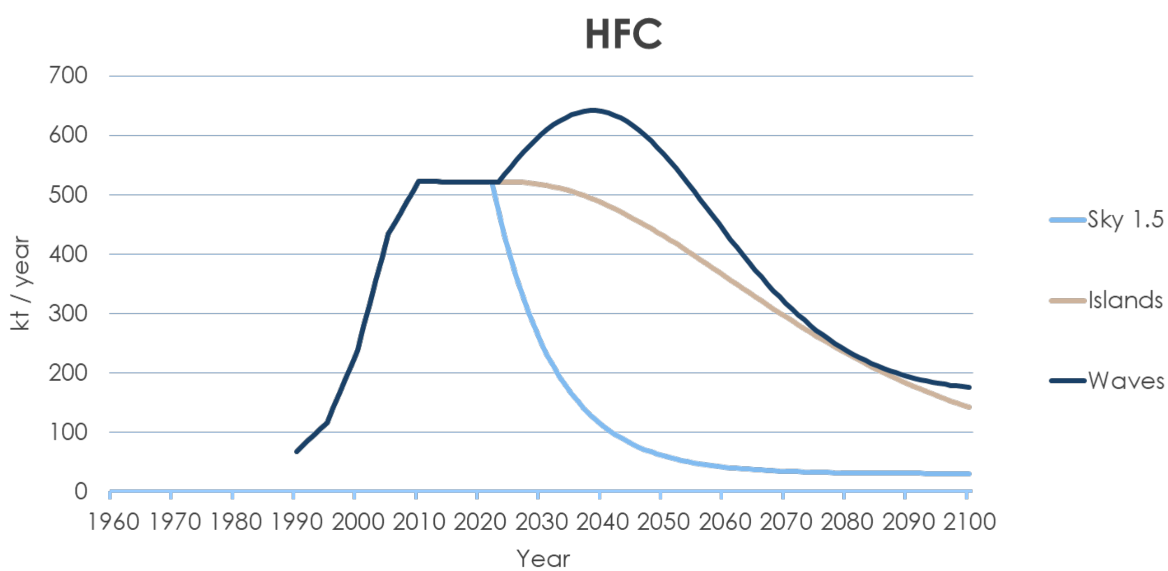

Figure A.7. HFC emissions

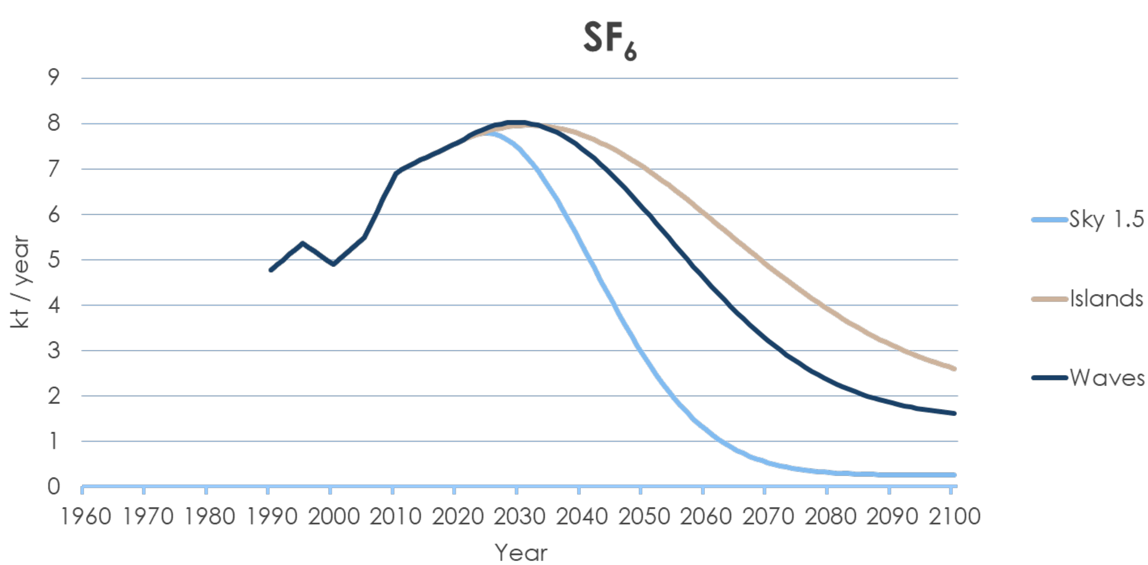

Figure A.8. SF_6 emissions

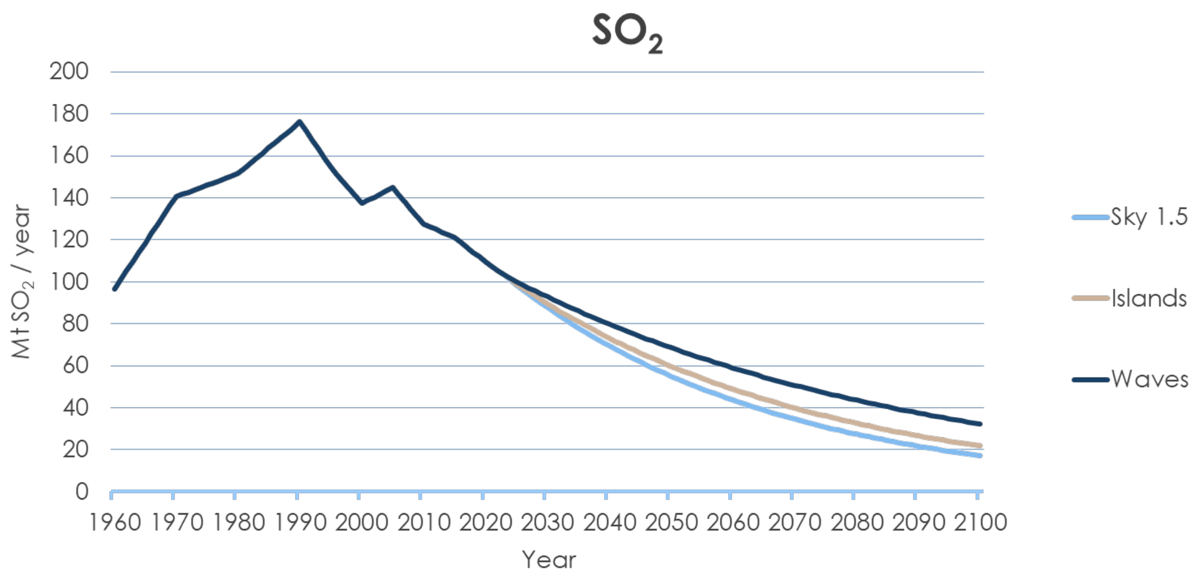

Figure A.9. SO_2 emissions

Appendix B. Temperature results for 400-run ensembles

Appendix B shows the results for the surface temperature increase for 400 runs of the *Islands*, *Waves* and *Sky 1.5* scenarios with different values of climate parameters. In comparison to Figures 8–10 that show probability bands, here we show the results for all 400 runs. The 400 samples are chosen from a probability distribution of climate parameters as described in Sokolov *et al.* (2018).

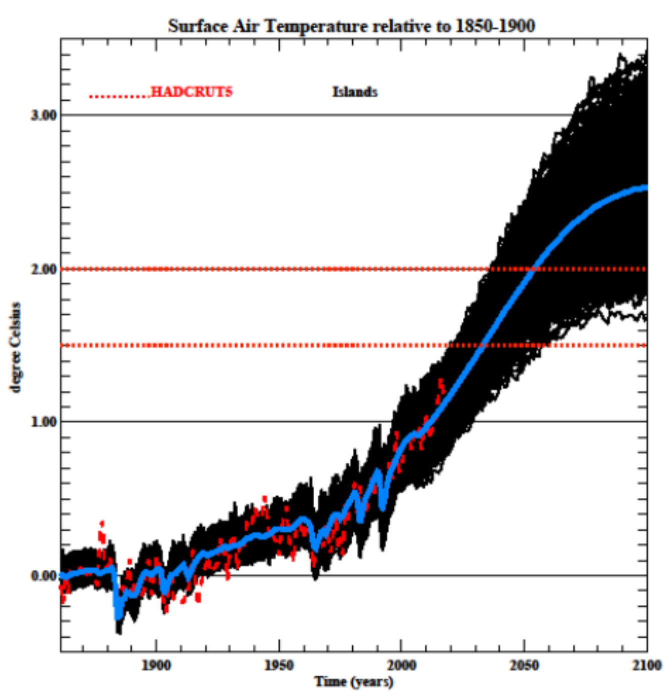

Figure B.1. 400-run ensemble results for the *Islands* scenario for global average surface air temperature change relative to the preindustrial level of 1850–1990 (C°). Blue line represents the mean of the ensemble.

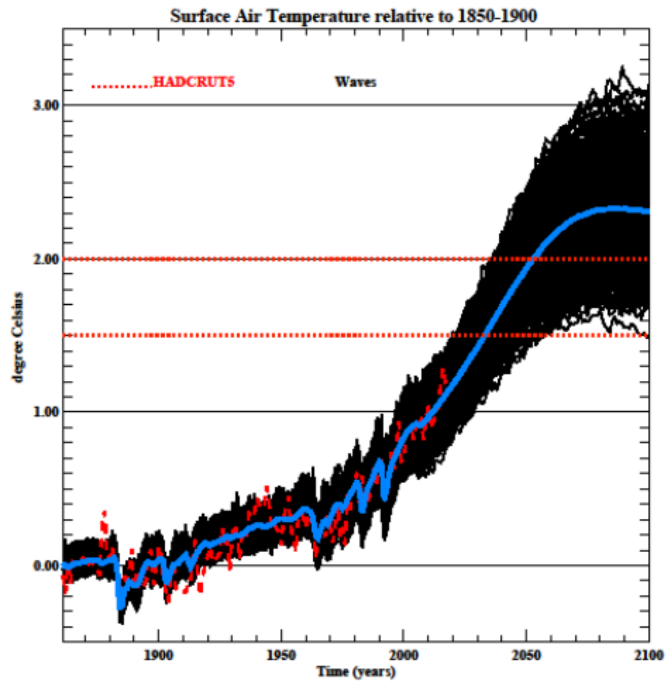

Figure B.2. 400-run ensemble results for the *Waves* scenario for global average surface air temperature change relative to the preindustrial level of 1850–1900 (C°). Blue line represents the mean of the ensemble.

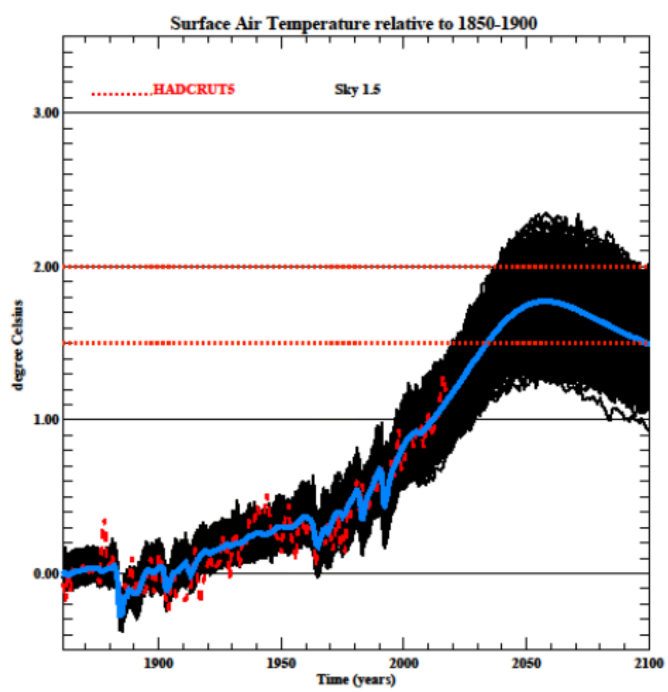

Figure B.3. 400-run ensemble results for the *Sky 1.5* scenario for global average surface air temperature change relative to the preindustrial level of 1850–1990 (C°). Blue line represents the mean of the ensemble.

Appendix C. Carbon uptake results for 400-run ensembles

Appendix C shows the results for terrestrial, ocean, and total carbon uptake for 400 runs of the *Islands*, *Waves* and *Sky 1.5* scenarios with different values of climate parameters.

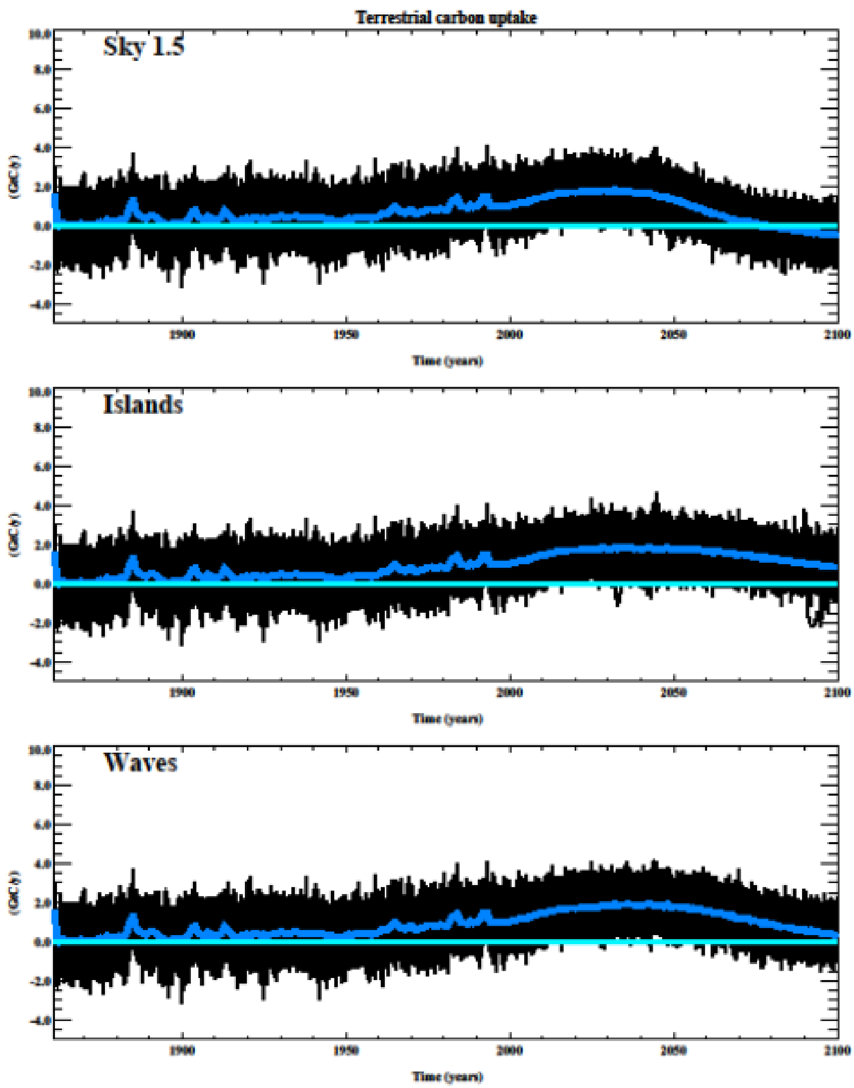

Figure C.1. 400-run ensemble results for terrestrial carbon uptake

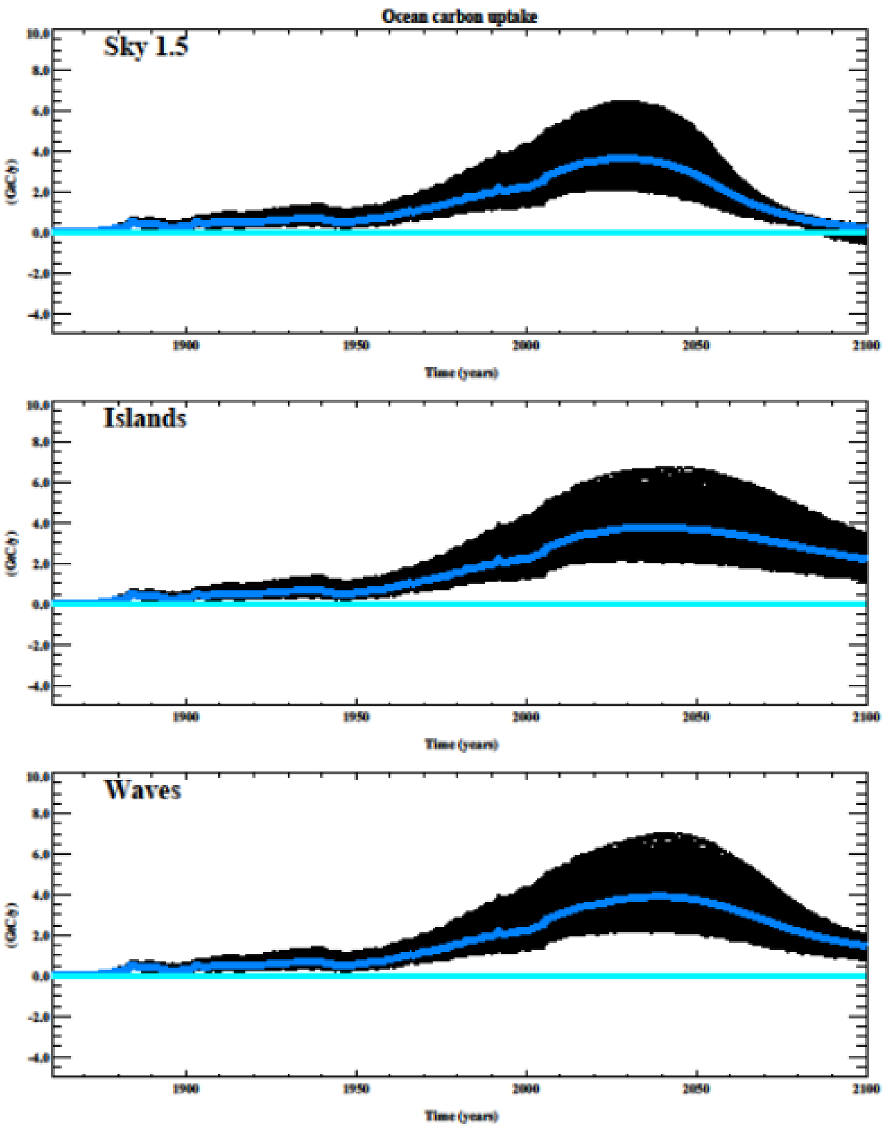

Figure C.2. 400-run ensemble results for ocean carbon uptake

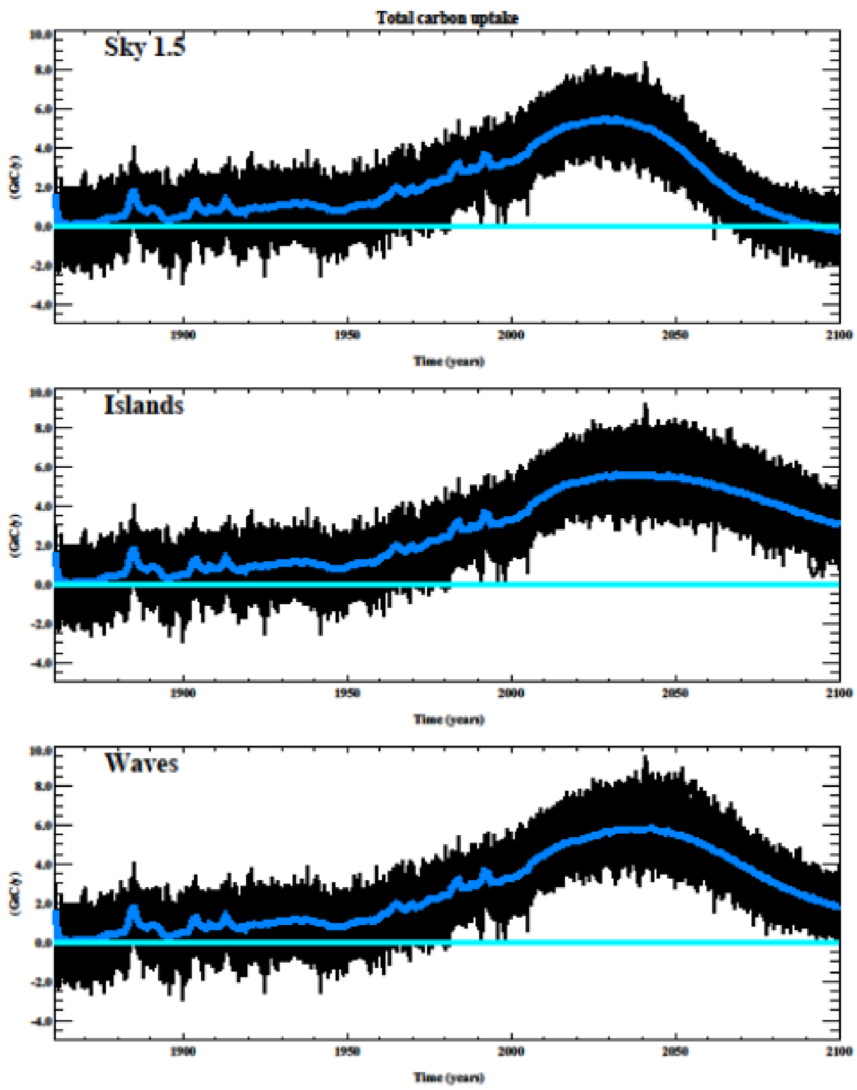

Figure C.3. 400-run ensemble results for total carbon uptake

Joint Program Report Series - Recent Articles

For limited quantities, Joint Program Reports are available free of charge. Contact the Joint Program Office to order.
Complete list: http://globalchange.mit.edu/publications

348. Changing the Global Energy System: Temperature Implications of the Different Storylines in the 2021 Shell Energy Transformation Scenarios. *Paltsev et al., Feb 2021*

347. Representing Socio-Economic Uncertainty in Human System Models. *Morris et al., Feb 2021*

346. Renewable energy transition in the Turkish power sector: A techno-economic analysis with a high-resolution power expansion model, TR-Power. *Kat, Feb 2021*

345. The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5°C or 2°C world. *Fajardy et al., Nov 2020*

344. Future energy: In search of a scenario reflecting current and future pressures and trends. *Morris et al., Nov 2020*

343. Challenges in Simulating Economic Effects of Climate Change on Global Agricultural Markets. *Reilly et al., Aug 2020*

342. The Changing Nature of Hydroclimatic Risks across South Africa. *Schlosser et al., Aug 2020*

341. Emulation of Community Land Model Version 5 (CLM5) to Quantify Sensitivity of Soil Moisture to Uncertain Parameters. *Gao et al., Feb 2020*

340. Can a growing world be fed when the climate is changing? *Dietz and Lanz, Feb 2020*

339. MIT Scenarios for Assessing Climate-Related Financial Risk. *Landry et al., Dec 2019*

338. Deep Decarbonization of the U.S. Electricity Sector: Is There a Role for Nuclear Power? *Tapia-Ahumada et al., Sep 2019*

337. Health Co-Benefits of Sub-National Renewable Energy Policy in the U.S. *Dimanchev et al., Jun 2019*

336. Did the shale gas boom reduce US CO_2 emissions? *Chen et al., Apr 2019*

335. Designing Successful Greenhouse Gas Emission Reduction Policies: A Primer for Policymakers – The Perfect or the Good? *Phillips & Reilly, Feb 2019*

334. Implications of Updating the Input-output Database of a Computable General Equilibrium Model on Emissions Mitigation Policy Analyses. *Hong et al., Feb 2019*

333. Statistical Emulators of Irrigated Crop Yields and Irrigation Water Requirements. *Blanc, Aug 2018*

332. Turkish Energy Sector Development and the Paris Agreement Goals: A CGE Model Assessment. *Kat et al., Jul 2018*

331. The economic and emissions benefits of engineered wood products in a low-carbon future. *Winchester & Reilly, Jun 2018*

330. Meeting the Goals of the Paris Agreement: Temperature Implications of the Shell Sky Scenario. *Paltsev et al., Mar 2018*

329. Next Steps in Tax Reform. *Jacoby et al., Mar 2018*

328. The Economic, Energy, and Emissions Impacts of Climate Policy in South Korea. *Winchester & Reilly, Mar 2018*

327. Evaluating India's climate targets: the implications of economy-wide and sector specific policies. *Singh et al., Mar 2018*

326. MIT Climate Resilience Planning: Flood Vulnerability Study. *Strzepek et al., Mar 2018*

325. Description and Evaluation of the MIT Earth System Model (MESM). *Sokolov et al., Feb 2018*

324. Finding Itself in the Post-Paris World: Russia in the New Global Energy Landscape. *Makarov et al., Dec 2017*

323. The Economic Projection and Policy Analysis Model for Taiwan: A Global Computable General Equilibrium Analysis. *Chai et al., Nov 2017*

322. Mid-Western U.S. Heavy Summer-Precipitation in Regional and Global Climate Models: The Impact on Model Skill and Consensus Through an Analogue Lens. *Gao & Schlosser, Oct 2017*

321. New data for representing irrigated agriculture in economy-wide models. *Ledvina et al., Oct 2017*

320. Probabilistic projections of the future climate for the world and the continental USA. *Sokolov et al., Sep 2017*

319. Estimating the potential of U.S. urban infrastructure albedo enhancement as climate mitigation in the face of climate variability. *Xu et al., Sep 2017*

318. A Win-Win Solution to Abate Aviation CO_2 emissions. *Winchester, Aug 2017*

317. Application of the Analogue Method to Modeling Heat Waves: A Case Study With Power Transformers. *Gao et al., Aug 2017*

316. The Revenue Implications of a Carbon Tax. *Yuan et al., Jul 2017*

315. The Future Water Risks Under Global Change in Southern and Eastern Asia: Implications of Mitigation. *Gao et al., Jul 2017*

314. Modeling the Income Dependence of Household Energy Consumption and its Implications for Climate Policy in China. *Caron et al., Jul 2017*

MIT Joint Program on the Science and Policy of Global Change

Massachusetts Institute of Technology
77 Massachusetts Ave., E19-411
Cambridge MA 02139-4307 (USA)

T (617) 253-7492 **F** (617) 253-9845
globalchange@mit.edu
http://globalchange.mit.edu/