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Temperature Implications of the 2023 Shell Energy Security Scenarios: Sky 2050 and Archipelagos

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

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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

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GLOBAL CHANGE

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Abstract: We analyze temperature implications of energy security-focused scenarios developed by Shell. The *Sky 2050* scenario explores the world developing in increasingly sustainable directions, with the corresponding energy needs for a global net-zero CO_2 target achieved by the year 2050. In contrast, the *Archipelagos* scenario sees the ongoing energy transition facing a mixture of support and hindrance by geopolitics and security steady technological development continues. 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 relative to pre-industrial (mean of 1850-1900) levels. Our analysis shows that the *Sky 2050* scenario is an overshoot 1.5°C scenario (category C2 by the definition of the Intergovernmental Panel on Climate Change). Global surface temperature (ensemble median) in this scenario stays above 1.5°C for 40 years, from 2034 to 2073, reaches its peak of 1.67°C in 2051, and then declines to 1.24°C by 2100. For the *Archipelagos* scenario, mean temperature passes 1.5°C in 2033, 2°C in 2060, and reaches 2.22°C in 2100. We find that likely (33-66%) range in 2100 is 1.16-1.33°C for the *Sky 2050* scenario and 2.10-2.33°C for the *Archipelagos* scenario. The corresponding very likely (5%-95%) ranges are 0.97-1.56°C and 1.73-2.72°C, respectively.

1. Introduction

The Paris Agreement (UN, 2015) established 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. The Glasgow Climate Pact (UN, 2021) recognized that limiting global warming to 1.5°C means net-zero CO_2 emissions by mid-century. A recent assessment report by the International Panel on Climate Change (IPCC, 2022) warned that global greenhouse gas (GHG) emissions associated with the implementation of Nationally Determined Contributions announced in 2021 (prior to COP26) would make it likely that warming will exceed 1.5°C during the 21st century. At COP27 in 2022, countries have been encouraged to accelerate their mitigation efforts because an emission gap still exists between current national climates plans and what is needed to keep global temperature rise to 2°C or 1.5°C (UNFCCC, 2022).

While globally coordinated climate policy designed to achieve this goal is still not in place, growing pressure from society moves the world towards decarbonization. These 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.*, 2023). These trends drive a transition in the energy system that leads to fewer emissions. Energy scenarios are important to assess the energy system transition required to mitigate climate challenges and to guide policy makers and industry leaders. Shell has a long history of applying scenario analysis to explore how the choices today will shape the future energy landscape. Temperature implications of earlier Shell scenarios are explored in Prinn *et al* (2011) and Paltsev *et al* (2018, 2021).

The goal of this paper is to provide an assessment of temperature implications of the latest Shell scenarios (Shell, 2023). 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).

To take in to account uncertainty in the Earth system response to anthropogenic emissions we carried out a set of ensembles of 400 climate simulations changing MESM parameters affecting climate response to external forcing, such as climate sensitivity, coefficient for vertical diffusion of heat into deep ocean, strength of aerosol forcing due to aerosol radiation interaction, and also parameters affecting strength of the carbon cycle. The 400 parameter samples were chosen from a probability distribution of climate parameters described in Sokolov *et al.* (2018).

The probability distribution for climate sensitivity as well as distributions for variables describing climate response, namely transient climate response (TCR) and transient climate response to cumulative carbon emissions (TCRE), shown in Sokolov *et al.* (2018), are in a good agreement with estimates presented in recent literature.

Climate simulations with MESM are carried out in two stages: historical simulations from 1861 to 2005 and forward climate simulations from 2006 to 2100. During the first stage, MESM is run in a concentration-driven mode forced by observed changes in natural and anthropogenic forcing. In the second stage, MESM is run in an emissions-driven mode and forced by anthropogenic GHG emissions. As such, we first carried out the ensemble of historical simulations and subsequently the ensembles for each of scenarios considered below.

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 concentrations and total radiative forcing. Section 5 discusses the temperature implications.

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 *Sky 2050* and *Archipelagos* scenarios developed by Shell (see Shell (2023) 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.

In the *Sky 2050* scenario, the world overcomes the impacts of the Covid-19 pandemic and responds to the Russian invasion of Ukraine by redoubling its focus on the health of public and the planet, reaching the goals of the Paris Agreement. Fossil fuels and associated CO_2 emissions are seen as part of the energy security problem. Any immediate response to a crisis to fall back on unabated CO_2 emissions is met with greater policy efforts to accelerate the energy transition. Regions and groupings of countries compete against each other driving decarbonization efforts.

The scenario design seeks to spread effort across the system – across regions, across sectors, and across technologies. There is recognition of some of the short-term momentum built into the energy system, but nevertheless, the individual and combined assumptions for Sky 2050 to reach net-zero CO_2 2050 are stretching. The resulting GHG emissions for the *Sky 2050* scenario are provided in **Figure 1**. Net GHG emissions have been growing from about 40 gigatonnes of CO_2-equivaent (Gt CO_2e) in 2000, but in this scenario they peak at about 57 Gt CO_2e in 2022, then they decline to zero in 2062, and stay below zero until 2100. The corresponding anthropogenic CO_2 emissions (that represent a sum of emissions from energy, industrial process and land use change) decline from their 2022 level of about 41 Gt CO_2, achieve net-zero in 2050, and stay negative in the second half of the century reaching a net sink of about 15 Gt CO_2 by 2100.

The *Archipelagos* scenario recognizes the rising pressure to address environmental concerns, including climate, and it takes an optimistic view that new energy technologies (e.g., carbon capture and storage, cellulosic biofuels, hydrogen, electrification of demand) emerge. However, the motivations wrestle with sometimes competing objectives for countries' and regions' security, brought into sharp focus following the Russian invasion of Ukraine. The scenario explores how different parts of the world have different priorities, leading to a greater phasing of action on environment between leaders and followers, than witnessed in *Sky 2050*. *Archipelagos* experiences headwinds from access to new mineral resources, from re-orienting of supply chains, and from customer and citizen acceptance of the priority for all aspects of the transition. Although the normal course of equipment and infrastructure replacement and the deployment of cleaner technologies bring progress and emission reductions, the world overshoots the timeline and does not achieve the goals of the Paris agreement. Instead, there is later and slower decarbonization.

The resulting GHG emissions for the *Archipelagos* scenario are illustrated in **Figure 2**. Net GHG emissions continue to grow and they peak around 2030 at 58 Gt CO_2e, then the emissions are fall at a similar rate at which they have risen in recent decades, reaching about 15 Gt CO_2e in 2100.

In the *Sky 2050* scenario, the initial response to the crises of 2020-2022 is to focus on responding to the pandemic and energy security. Lessons learned from best practices, alignments of common interests and competition in policy frameworks help create a pathway to health not only of

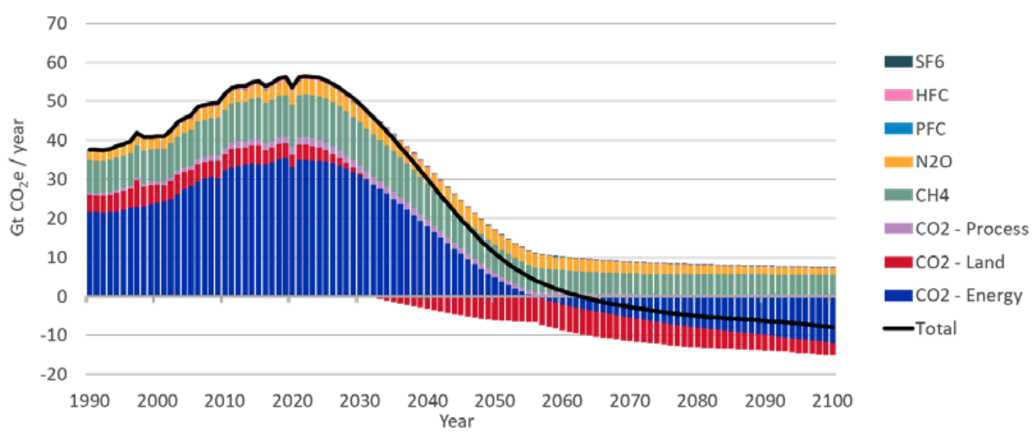

Figure 1. Global GHG Emissions in the *Sky 2050* Scenario

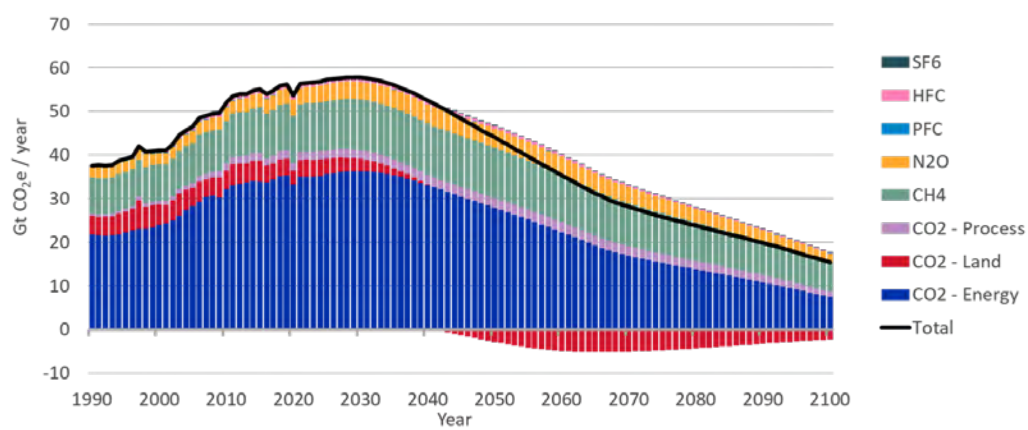

Figure 2. Global GHG Emissions in the *Archipelagos* Scenario

people and society, but also of the environment, including the extensive use of nature-based solutions (NBS) through the conservation, restoration, or improved management of natural ecosystems. The supply of high-quality NBS projects might be challenged by ecological, social and financial constraints. The *Sky 2050* scenario meets the Glasgow Deforestation Pledge to end deforestation by 2030.

To reflect potential issues with the deploying NBS at full scale, a sensitivity is developed where realization of NBS potential is delayed by 20 years. This sensitivity is called *Sky 2050 NBS Delay*, where land-use emissions are affected correspondingly. All other emissions in this scenario are the same as in the *Sky 2050* scenario. The resulting total anthropogenic CO_2 emissions are illustrated in **Figure 3**. In the *Sky 2050 NBS Delay* scenario, net-zero CO_2 target is achieved in 2056, which is six years later than in the *Sky 2050*.

Appendix A compares the trajectories for energy-related CO_2, industrial process CO_2, land-use change CO_2, non-CO_2 GHG gases (CH4, N2O, PFC, HFC, SF6), and SO2 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 2050* 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 *Archipelagos* scenario also sees some CCS applied in processes such as cement manufacture, but technology deployment is slower than in *Sky 2050*. 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 *Sky 2050* 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 2050* scenario giving rise to widespread NBS application, such as forestry and land management efforts with the land sink increasing to about 7 Gt CO_2 by 2057 and reducing afterwards to about 3 Gt CO_2 by 2100 as ultimate potentials for restoration are approached. Historically, 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 2031 in the *Sky 2050* scenario, in 2051 in the *Sky 2050 NBS Delay* scenario, and in 2041 in the *Archipelagos* scenario. The overall land sink is smaller in the *Archipelagos* scenario. It is at a maximum of about 5 Gt CO_2 by 2065 and reducing afterwards to about 2 Gt CO_2 by 2100. In Appendix B, we provide a comparison of the resulting total anthropogenic CO_2 emissions with the corresponding ranges for the 1.5°C scenarios from the IPCC AR6.

Methane (CH4) 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 2050* 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 lower in the *Sky 2050* scenario, but still around half peak levels.

Nitrous oxide (N2O) 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

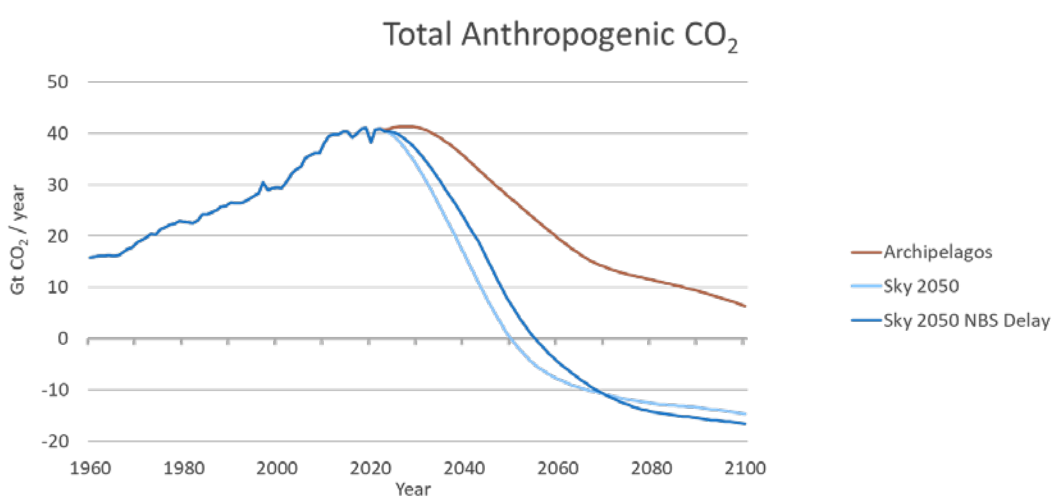

Figure 3. Global total (energy+industry+land use) anthropogenic CO_2 emissions in the *Archipelagos, Sky 2050,* and *Sky 2050 NBS Delay* scenarios

agricultural soil management. By the end of the century, the *Sky 2050* scenario sees the most progress through changes in agriculture and rapid sharing of best practices, including lowering fertilizer use.

Both scenarios build in the widespread consensus that abatement of methane and nitrous oxide will be more challenging than for CO_2. As such, in the *Sky 2050* scenario, meeting the goal of the Paris Agreement require extra effort on CO_2 rather than any lessening of the pressure through other GHG reductions. In both scenarios, the industrial gases are managed, but to differing extents. The *Sky 2050* scenario projects rapid reductions in PFCs, HFCs and SF6 as comprehensive actions are taken globally and alternative technologies are aggressively deployed. But in the *Archipelagos* scenario 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 scenarios from the Kigali Amendment to the Montreal Protocol. In all scenarios for all F-gases, emissions are down by 40% or more by 2100, with emissions in the *Sky 2050* scenario down by about 90% relative to the 2020 levels.

Sulphur dioxide (SO2) 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 both 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 2050* scenario is lowest for SO2 in 2100 with reduction of nearly 90% relative to the 2020 levels.

3. Carbon Emissions and Uptake

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

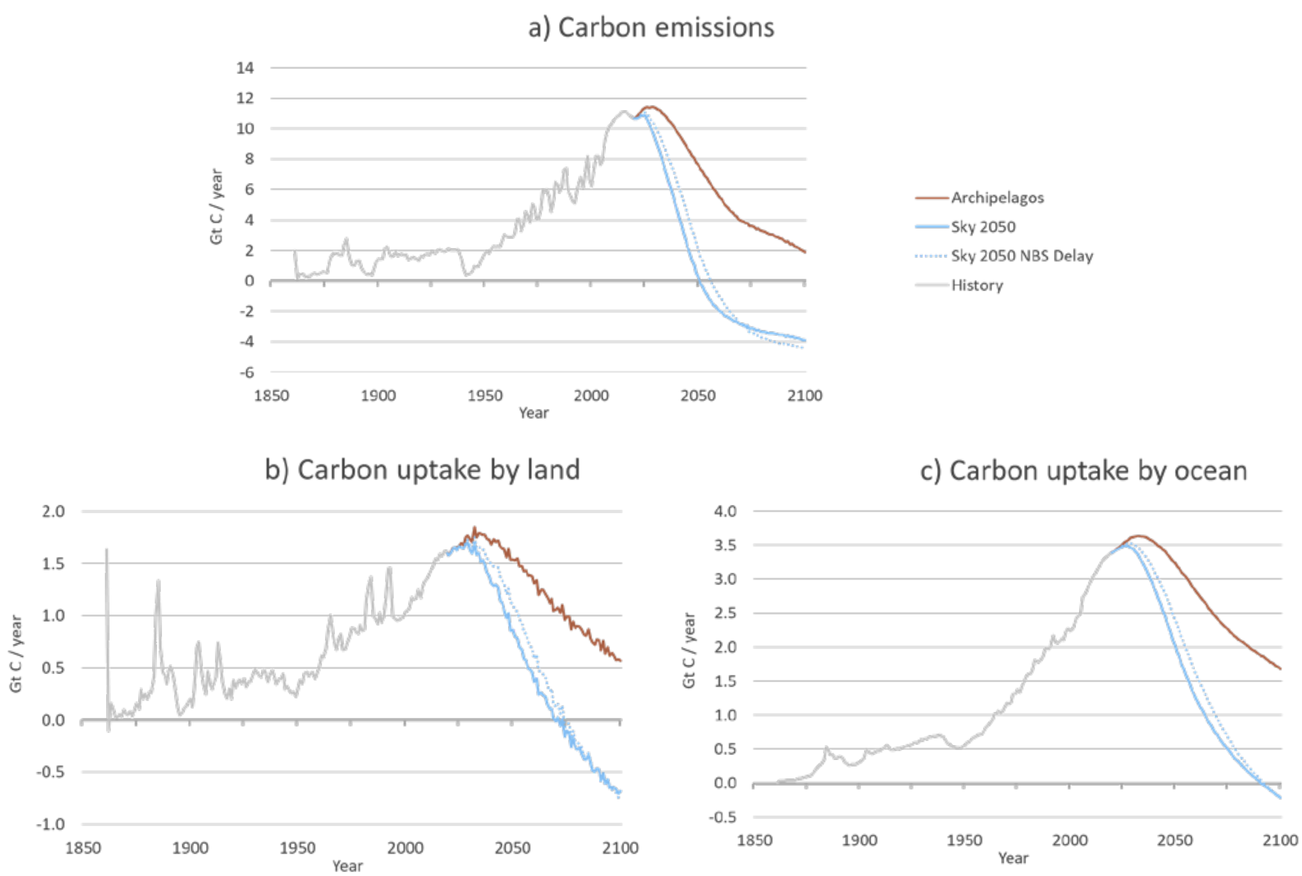

Figure 4. Carbon balance (in Gt C/year): Total net anthropogenic carbon emissions (panel a), land carbon uptake (panel b), ocean carbon uptake (panel c)

industrial emissions of CH4 and CO (that produce CO_2 with ~month to ~decade time delay). For this reason, the implied carbon emissions are shown in Figure 4. There is a noticeable difference between changes in emissions and uptake. Emissions peak at about 11.5 GtC/year while ensemble mean total uptakes peak at about 5.5 GtC/year. About 50% of emitted carbon remains in the atmosphere till year 2050 or 2040 for the *Archipelagos* and *Sky 2050* scenarios, respectively. Due to a significant lag between carbon uptake (especially by ocean) and changes in atmospheric CO_2 concentration, both ocean and terrestrial ecosystems are not in equilibrium with the atmospheric CO_2 level at the time when emissions start to decrease. Therefore, both ocean and land continue to take up carbon. Total carbon uptake remains positive in the *Archipelagos* scenario through 2100, but it becomes negative in 2082 for the *Sky 2050* scenario and in 2083 for the *Sky 2050 NBS Delay* scenario. The terrestrial ecosystem in the *Sky 2050* scenario becomes a carbon source in 2070 and in the *Sky 2050 NBS Delay* it comes a source in 2074 (Figure 4b). In contrast, carbon uptake by the ocean stays positive longer for all scenarios due to mixing of carbon into deep ocean. For the *Sky 2050* and *Sky 2050 NBS Delay* scenarios, ocean becomes a carbon source in 2092-2093 (Figure 4c).

In **Figure 5** we re-arrange the data from **Figure 4** and show the carbon fluxes of total anthropogenic carbon emissions and uptakes for the individual scenarios. By the end of the century, net carbon flux to the atmosphere becomes negative in the *Sky 2050* scenario and approaches zero in the *Archipelagos* scenario.

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 *Archipelagos* scenario, but become negative in the *Sky 2050*

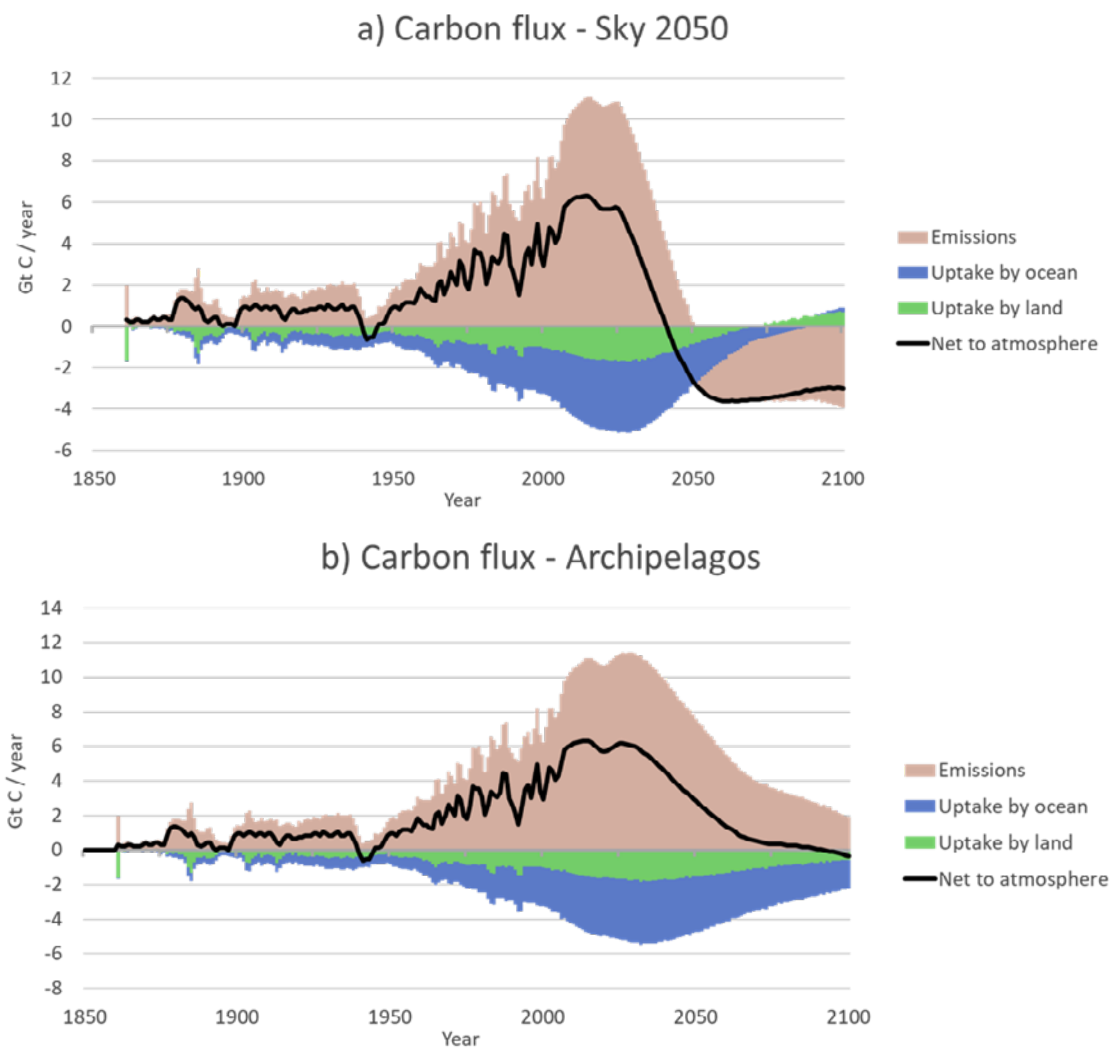

Figure 5. Carbon flux (in Gt C/year) for the *Sky 2050* scenario (panel a), the *Archipelagos* scenario (panel b)

and *Sky 2050 NBS Delay* scenarios. From the current CO_2 concentration of about 420 ppm, in the *Archipelagos* scenario CO_2 concentrations increase to about 510 ppm in 2100. In the *Sky 2050* scenario, they rise to about 458 ppm by 2041 and then decrease to about 370 ppm in 2100. In the *Sky 2050 NBS Delay* scenario, CO_2 concentrations increase to about 467 ppm by 2046 and then decrease to about 380 ppm in 2100

Figure 7 shows the calculated total radiative forcing relative to 1860 that account for radiative forcing by all GHGs and aerosols (sulphates, black carbon). Total radiative forcing rises from the current level of about 3.5 watts per square meter (W/m2). In the *Archipelagos* scenario, it increases to about 4.75 W/m2 in 2066 and then decreases to about 4.4 W/m2 in 2100. In the *Sky 2050* scenario, it rises to about 4.05 W/m2 by 2040 and then decrease to about 2.2 W/m2 in 2100. In the *Sky 2050 NBS Delay* scenario, total radiative forcing increases to about 4.15 W/m2 by 2042 and then decrease to about 2.35 W/m2 in 2100.

5. Temperature Implications

Changes of surface temperature are usually presented in terms of "global mean surface air temperature" (GSAT), which represents a global average of near-surface air temperatures over land and oceans. Another measure for temperature is "global mean surface temperature" (GMST), estimated as a global average of near-surface air temperatures over land and sea-ice, and sea surface temperatures over ice-free ocean regions. Changes in GSAT are often used as a measure of global temperature change in climate models, but they are not observed directly. Observational data, such as HadCRUT5 (Met Office, 2022), show temperature in terms of GMST. For a majority of models, their simulated historical GSAT increases faster than GMST (Rogelj *et al.*, 2019), and his-

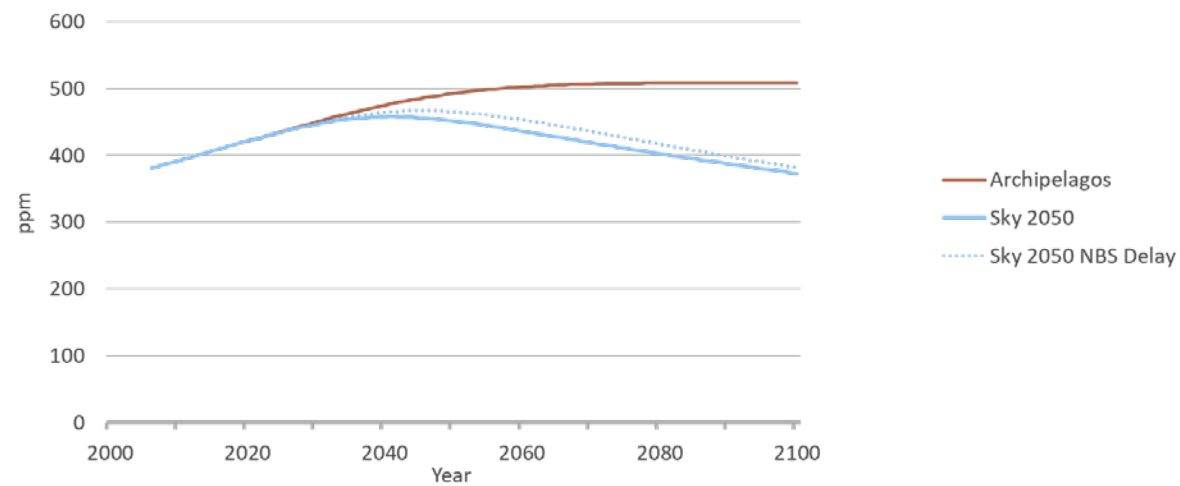

Figure 6. Atmospheric CO_2 concentrations (mole fractions in ppm CO_2)

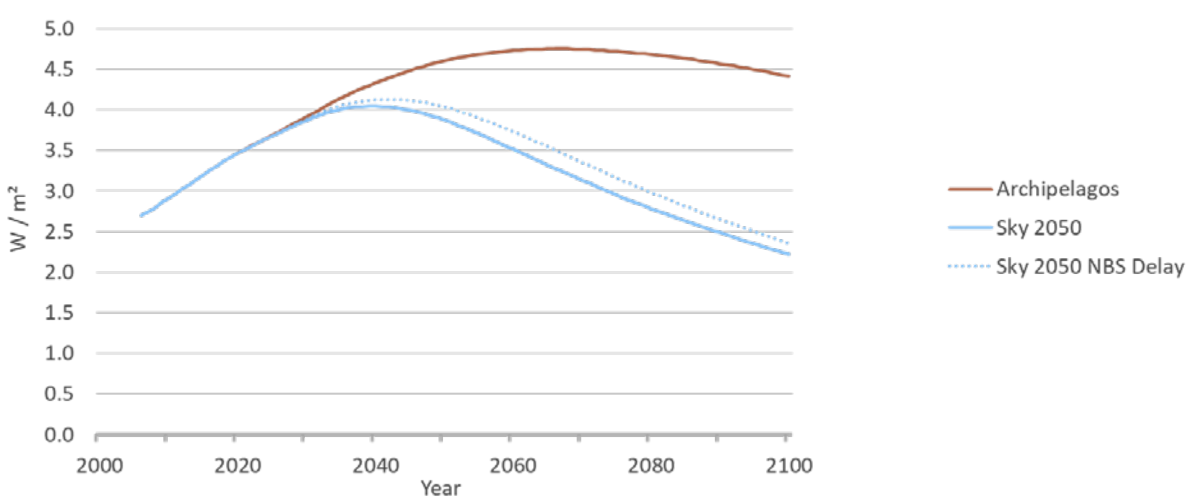

Figure 7. Total radiative forcing (watts per square meter) computed for all GHGs and aerosols

torical warming in terms of GSAT is calculated by adjusting observations upward by about 0.1°C.

The IPCC AR6 report (IPCC, 2021) states that models likely overestimate GSAT increase. In the Executive Summary of Chapter 2, it is summarized that: *"Changes in GMST and global surface air temperature (GSAT) over time differ by at most 10% in either direction (high confidence), and the long-term changes in GMST and GSAT are presently assessed to be identical."* In MESM simulations, GSAT also increases faster than GMST during both concentration-driven and emissions-driven stages; therefore, in this report we present the temperature changes in terms of GMST.

As mentioned, MESM historical simulations start from the year 1861, and the changes in the global annual mean surface temperature are calculated relative to a mean of 1861-1880. For the purposes of consistency with the latest IPCC reporting, we convert the temperature results to be relative to a mean of 1850-1900 using the difference between two base periods from HadCRUT5 dataset (Met Office, 2022). 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. The ensemble median temperature in 2100 exceeds pre-industrial levels by 1.24°C, 1.32°C, and 2.22°C for the *Sky 2050, Sky 2050 NBS Delay* and *Archipelagos* scenarios, respectively.

Temperature in the *Sky 2050* scenario peaks at 1.67°C in 2051, while the peak in the *Sky 2050 NBS Delay* scenario is 0.07°C higher, and four years later, at 1.73°C in 2055. The temperature in 2100 is nearly 0.1°C higher than Sky 2050. Further, this case may have greater consequences due to biodiversity loss. Scientists estimate that a million species are at risk of extinction, within decades, on current trends in land-use (IPBES, 2019). We also can estimate the year when the indicative threshold of 1.5°C will be exceeded. The global mean surface temperature increase of 1.5°C is passed in little more than 10 years (in 2034 in *Sky 2050* and in 2033 in *Archipelagos*). Appendix C provides a discussion of the remaining carbon budgets.

Figure 9 shows the results for the global temperature change for 400 runs of the *Sky 2050* and *Archipelagos* scenarios, each run with different values of climate parameters. The 90% probability ranges (5%-95%) for the temperate change in 2100 relative to a mean of 1850-1900 are as follows: 0.97-1.56°C for the *Sky 2050* scenario and 1.73-2.72°C for the *Archipelagos* scenario. The 33% probability ranges (33%-66%) are as follows: 1.16-1.33°C for the *Sky 2050* scenario and 2.10-2.33°C for the *Archipelagos* scenario.

Another way of illustrating the likelihood of reaching various temperature increases relative to preindustrial levels is provided in **Figure 10**, which shows the cumulative probability density. As seen in the figure, the *Sky 2050* scenario has an 88% probability of remaining below 1.5°C and 100% probability of remaining below 2°C in the last five years of the 21st century relative to the 1850–1900 mean. We also calculate probability of peak temperature staying below a certain temperature level. For the *Sky 2050* scenario, probability of peak temperature staying below 1.5°C is only 18% and 95% for 2°C.

Figure 10 also illustrates probabilities of staying below 1.5°C, 2°C and 3°C for the *Sky 2050 NBS Delay* and the *Archipelagos* scenarios. They are 76%, 100%, 100% for the *Sky 2050 NBS Delay*, and 0%, 22%, 100% for the *Archipelagos* scenario, respectively.

6. Conclusions

In this paper, we have analyzed emissions and temperature implications of three scenarios of energy transition devel-

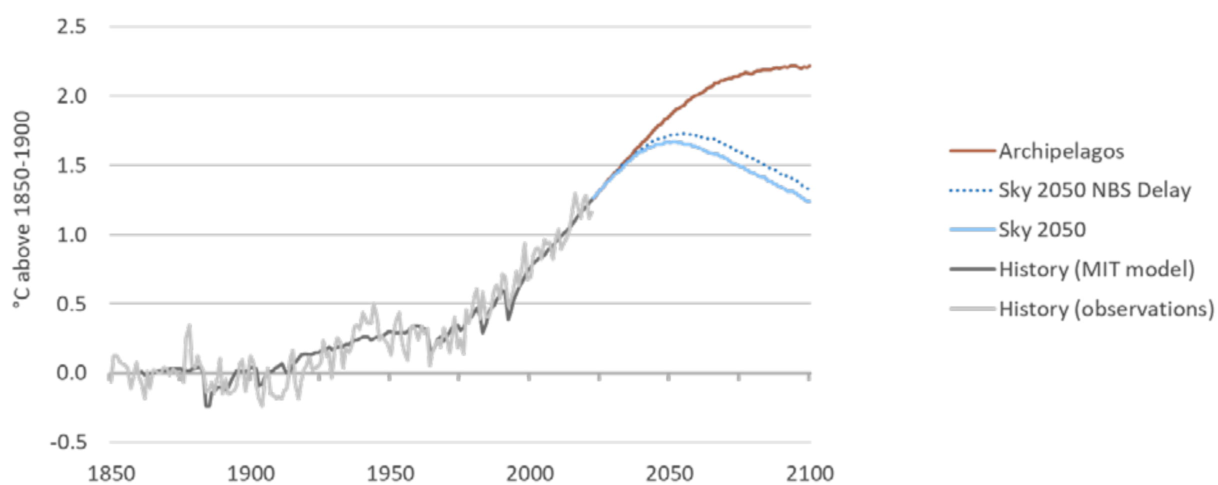

Figure 8. Global mean surface temperature (GMST, ensemble medians) change relative to the preindustrial level of 1850-1990 (°C). Observations: HadCRUT5 dataset (Met Office, 2022).

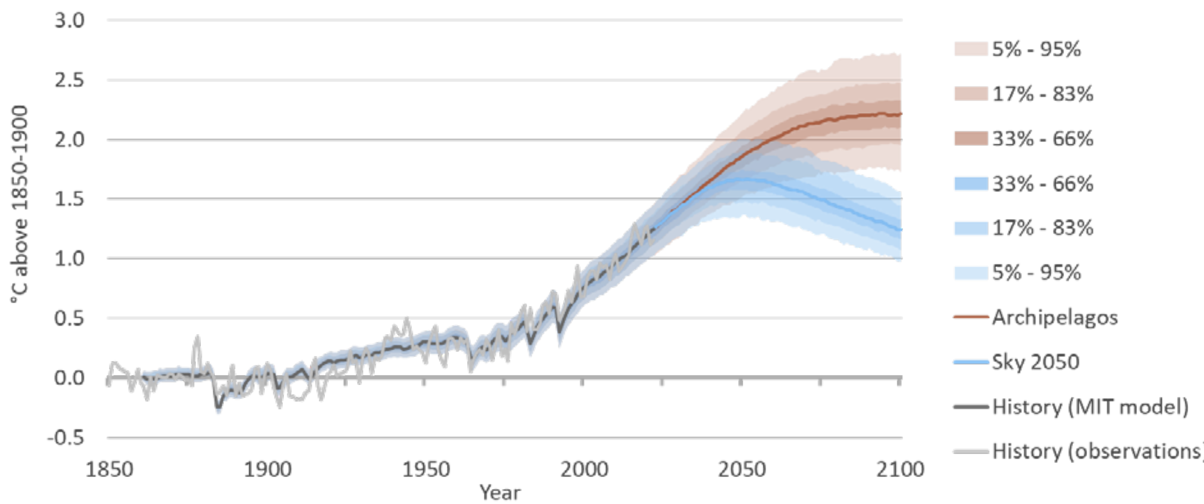

Figure 9. 400-run ensemble results for the *Sky 2050* and *Archipelagos* scenarios for global mean surface temperature change relative to the preindustrial level of 1850–1900 (C°). Darker shaded area represents 33-66% probability bound, medium shaded area represents 17-83% probability bound, and lighter shaded area represents 5-95% probability bound.

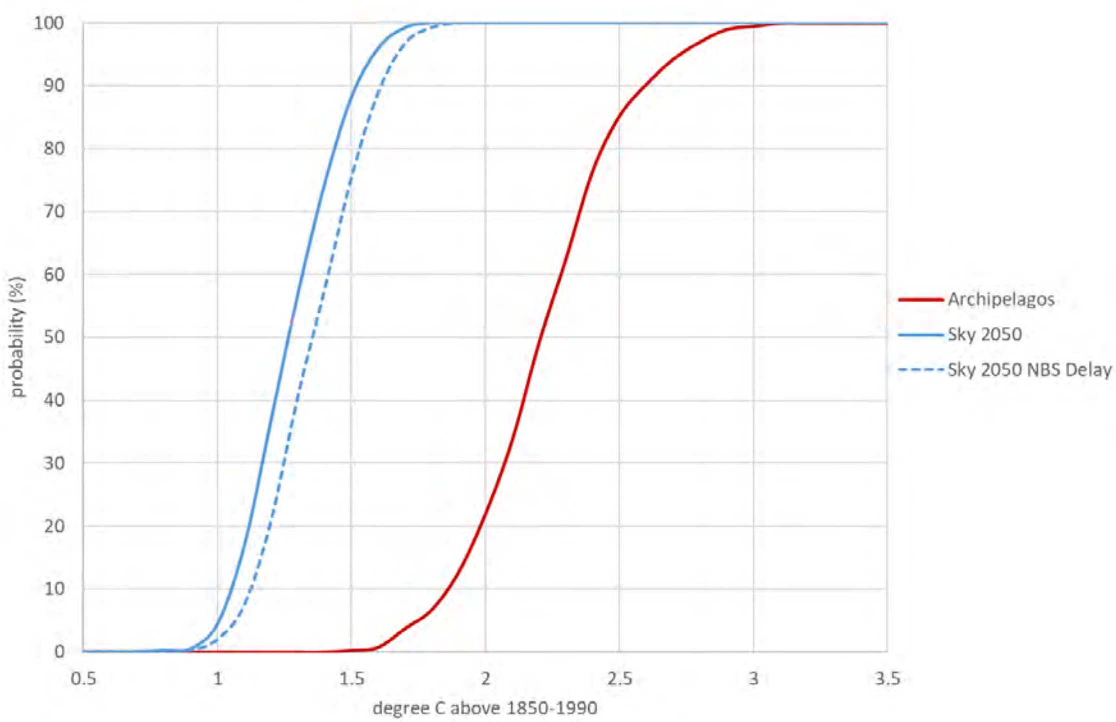

Figure 10. Probability (%) that global mean surface temperature in the last five years of the 21st century remains below given values (relative to 1850-1900 mean)

oped by Shell. 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 *Sky 2050* and *Archipelagos* scenarios by 2100. We find that, the ensemble mean global mean surface temperature increases above the pre-industrial levels by 2100 by 1.24°C for the *Sky 2050* scenario, and by 2.22°C for the *Archipelagos* scenario.

Our analysis shows that the *Sky 2050* scenario is an overshoot 1.5°C scenario (category C2 by the definition of the Intergovernmental Panel on Climate Change (IPCC, 2022)). Global surface temperature (ensemble median) in this scenario stays above 1.5°C for 40 years, from 2034 to 2073, reaches its peak of 1.67°C in 2051, and then declines to 1.24°C by 2100. In the *Sky 2050* scenario, the temperature in 2100 is almost exactly the same as the world experiences today. Delaying nature-based solutions (NBS) implementation by 20 years results in the peak temperature 0.07°C higher, and the peak is four years later, at 1.73°C in 2055. The temperature in 2100 in the delayed NBS scenario is nearly 0.1°C higher than in the *Sky 2050*.

The *Archipelagos* scenario passes 1.5°C in 2033, 2°C in 2060, and reaches 2.22°C in 2100. We find that likely (33-66%) range in 2100 is 1.16-1.33°C for the *Sky 2050* scenario and 2.10-2.33°C for the *Archipelagos* scenario. The corresponding very likely (5%-95%) ranges are 0.97-1.56°C and 1.73-2.72°C, respectively, for these scenarios. By presenting different potential energy futures and their resulting impacts on emissions and temperature, these scenarios can help inform government and industry decisions.

Acknowledgement

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Appendix A. GHG emission profiles

Appendix A provides a comparison of trajectories for emissions for individual GHG gases and SO2 in the *Sky 2050* and *Archipelagos* scenarios.

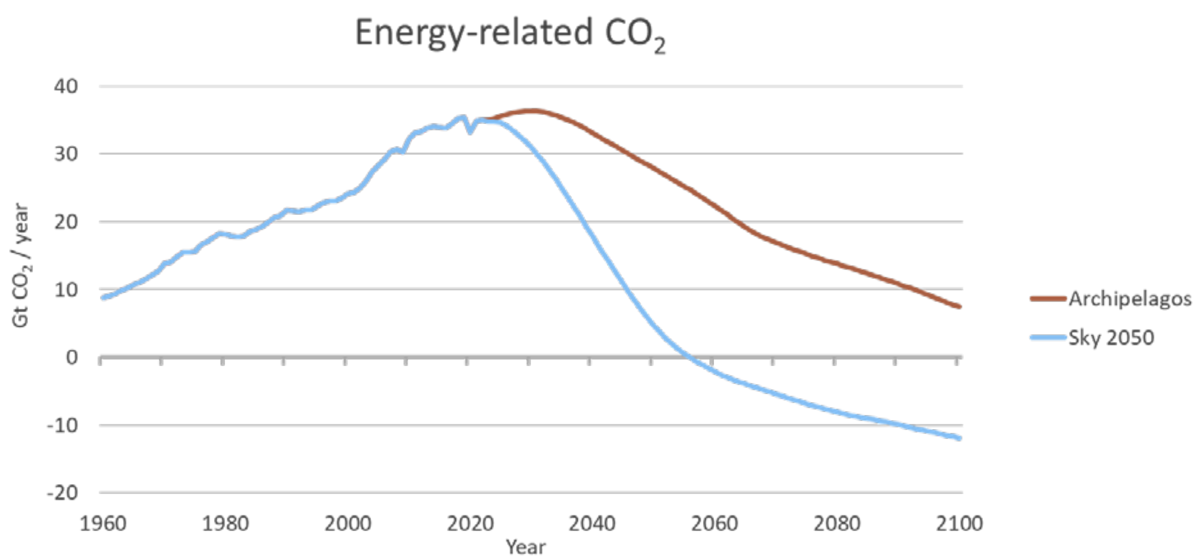

Figure A.1. Energy-related CO_2 emissions

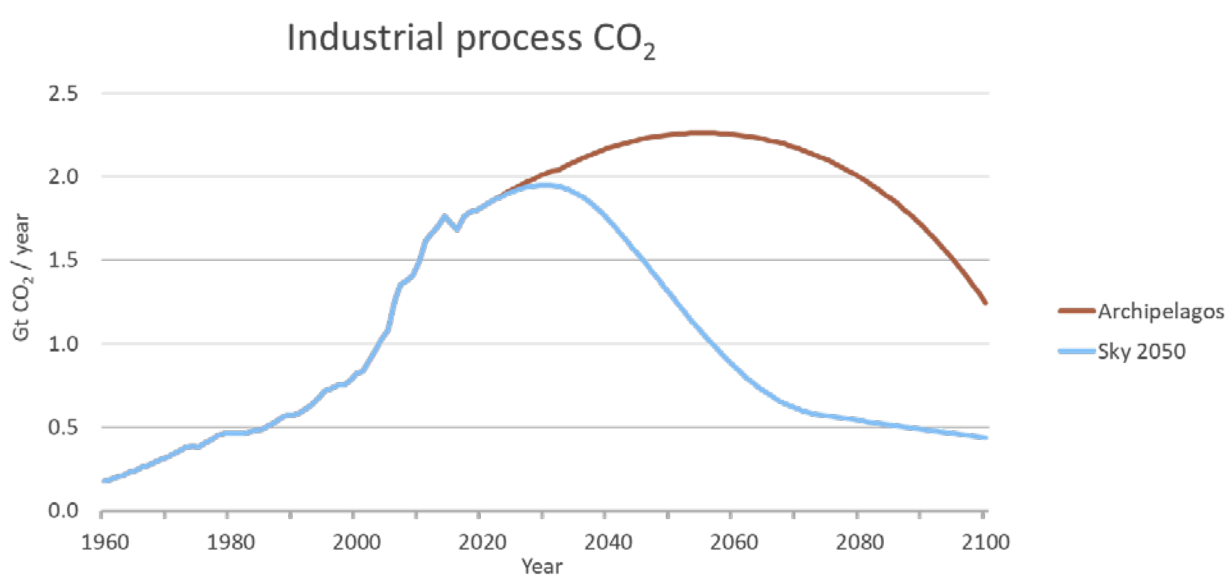

Figure A.2. Industrial CO_2 emissions

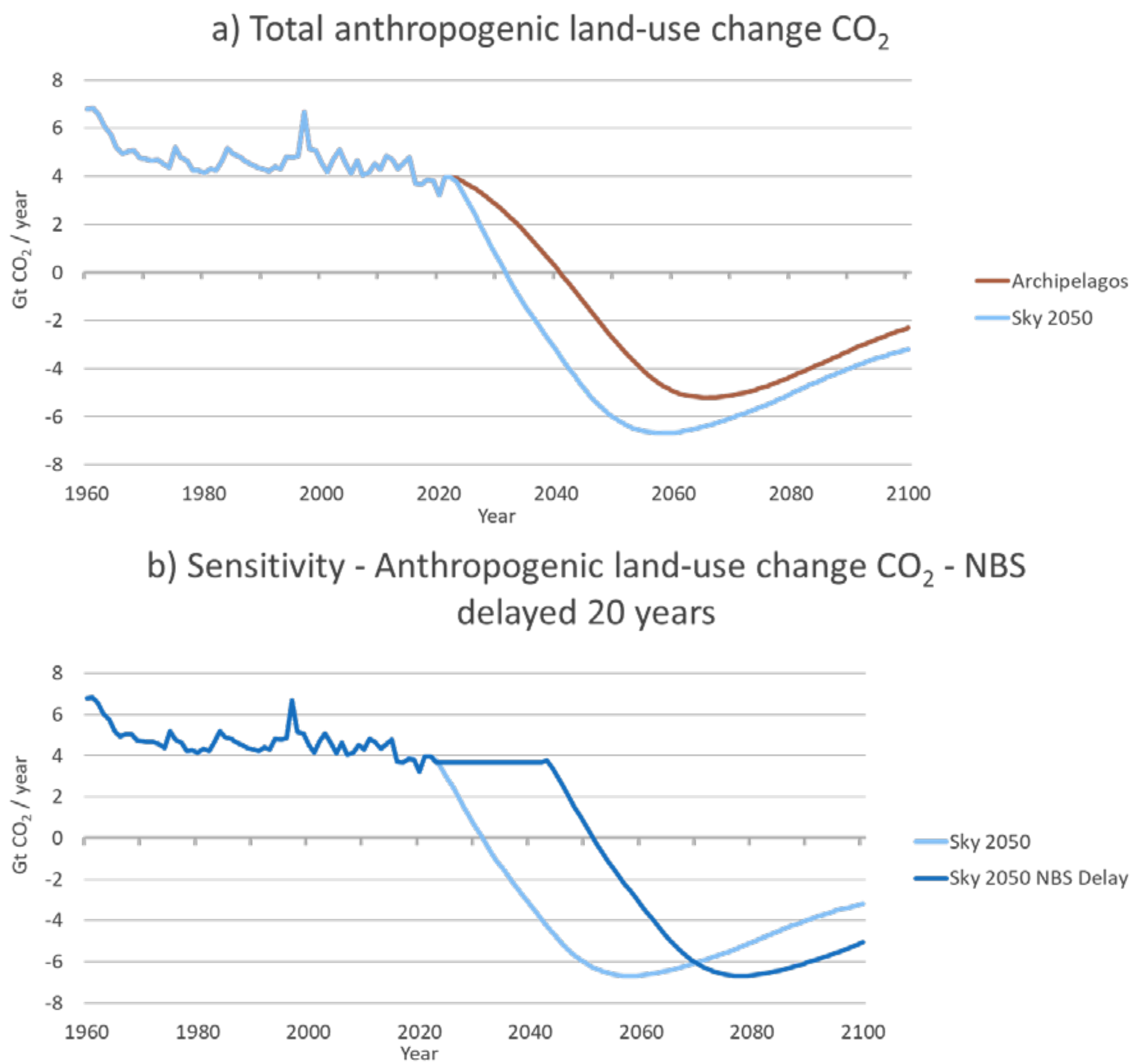

Figure A.3. Land-use change CO_2 emissions

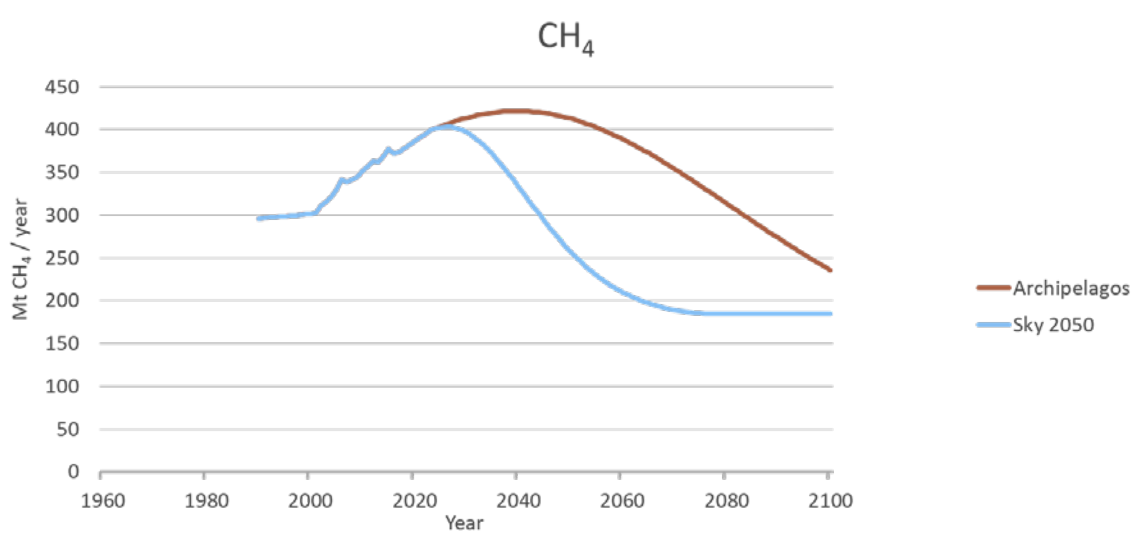

Figure A.4. CH4 emissions

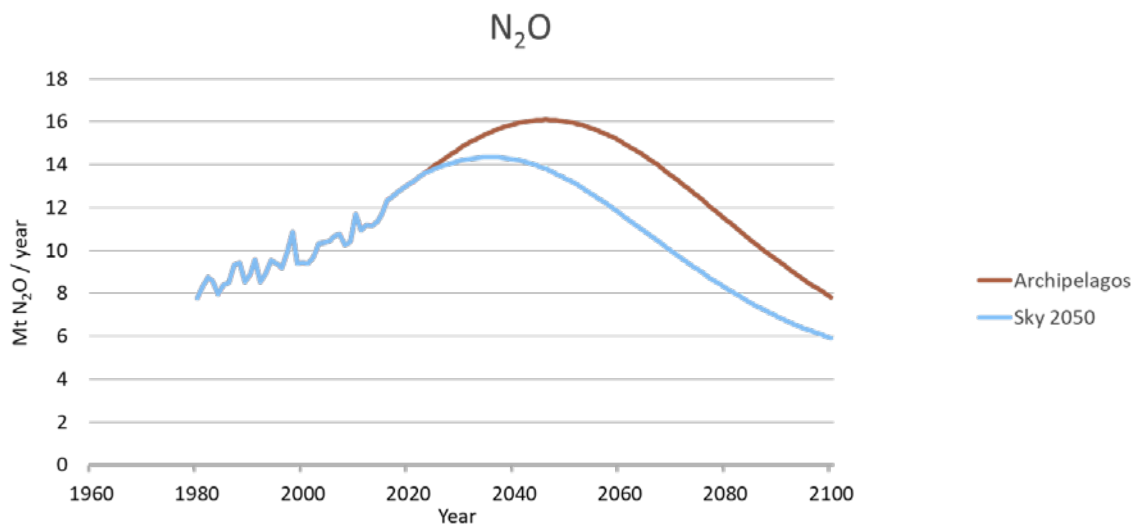

Figure A.5. N2O emissions

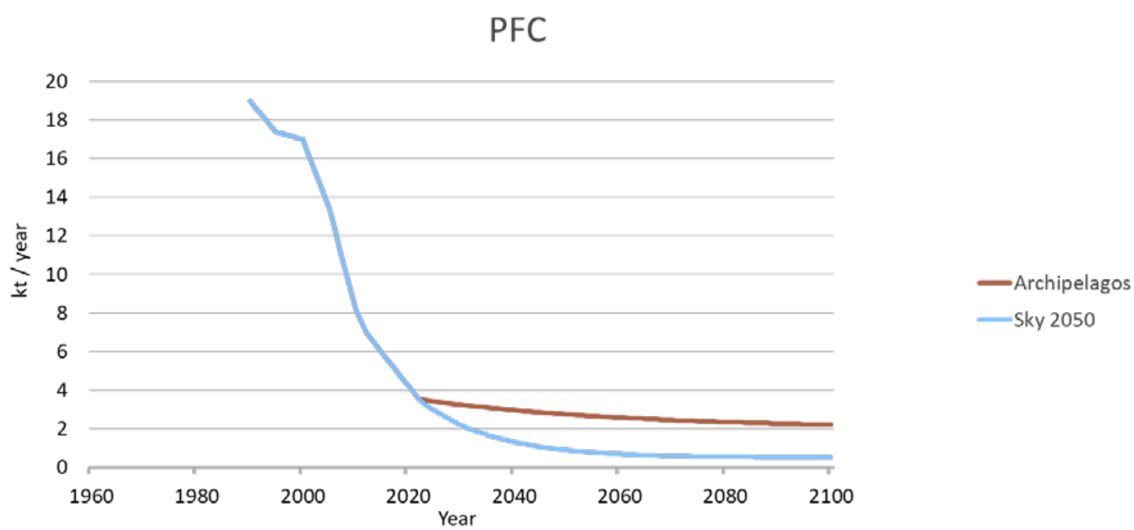

Figure A.6. PFC emissions

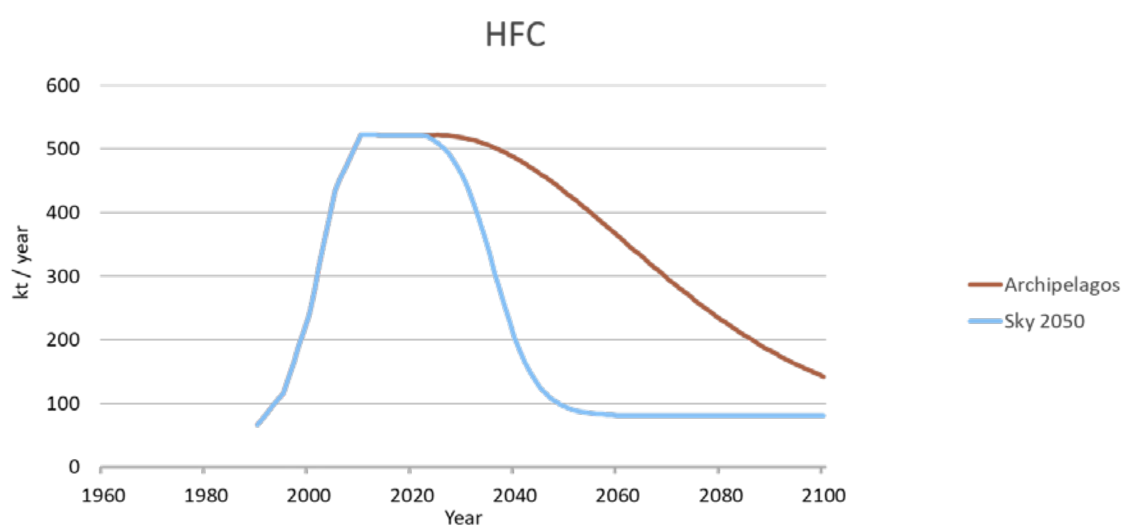

Figure A.7. HFC emissions

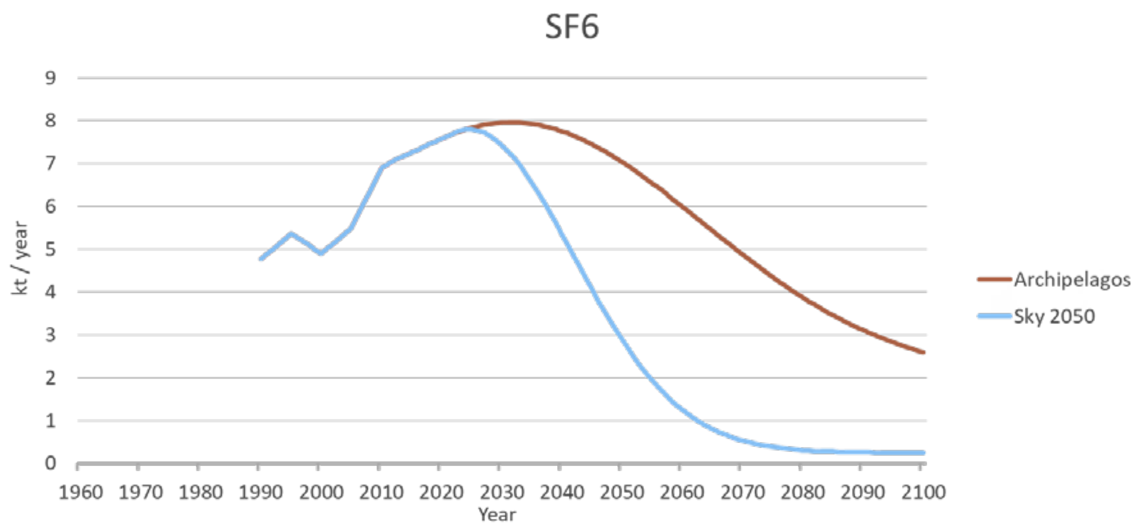

Figure A.8. SF6 emissions

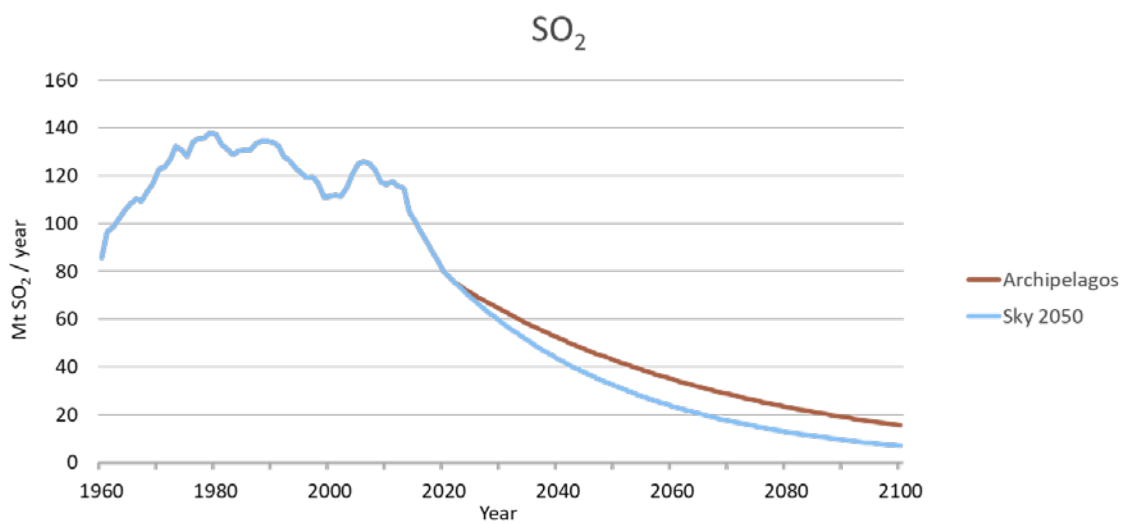

Figure A.9. SO2 emissions

Appendix B. Total CO_2 emission profiles in the *Sky 2050* and *Archipelagos* scenarios compared with IPCC 1.5°C scenarios

Appendix B provides a comparison of trajectories of emissions for total (i.e., energy-related plus industrial plus land use) anthropogenic CO_2 in the *Sky 2050* and *Archipelagos* scenarios with the corresponding full ranges from C1 and C2 categories of the IPCC AR6 scenarios. Both C1 and C2 scenarios represent the paths to limit the global warming to 1.5°C. Scenarios in the C1 category limit warming to 1.5°C (>50%) with no or limited overshoot, while the scenarios in the C2 category return warming to 1.5°C (>50%) after a high overshoot. Figure A.10 illustrates that the *Sky 2050* scenario fits well withing the C2 range.

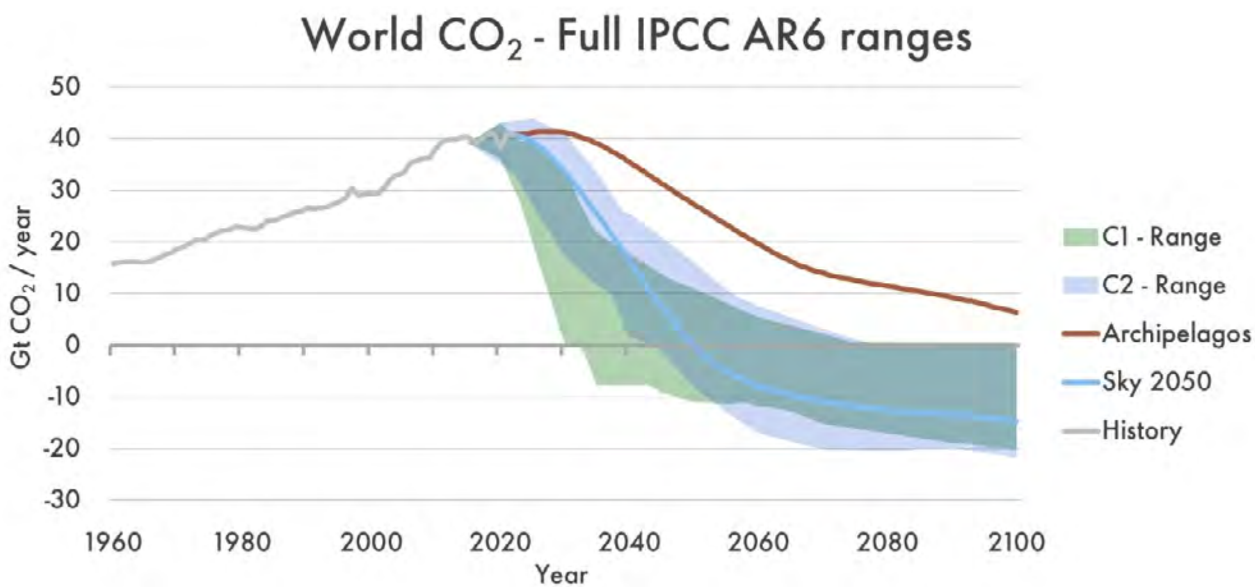

Figure A.10. Total anthropogenic CO_2 emissions in the *Sky 2050* and *Archipelagos* scenarios compared to C1 and C2 ranges from IPCC AR6

Appendix C. Carbon budgets in the *Sky 2050* and *Archipelagos* scenarios compared with IPCC estimates

A number of approaches for estimating carbon budgets corresponding to different global warming levels are discussed in the recent assessment report by the Intergovernmental Panel on Climate Change (IPCC, 2021). Estimates of the remaining carbon budgets, presented in Chapter 5 of AR6 WGI, are based on the estimated values of transient climate response to cumulative carbon emission (TCRE), zero emissions commitment (ZEC, defined as amount of warming projected to occur following a complete cessation of carbon emissions), historical warming (2010-2019 mean), and non-CO_2 warming, using the following equation:

$$B_{\mathrm{lim}} = (T_{\mathrm{lim}} - T_{\mathrm{hist}} - T_{\mathrm{nonCO2}} - T_{\mathrm{ZEC}}) / TCRE - E_{\mathrm{Esfb}},$$

where B_{lim} is the remaining carbon budget, T_{lim} is a specific temperature change limit, T_{hist} is historical human-induced warming to date, T_{nonCO2} is the non-CO_2 contribution to future temperature rise, T_{ZEC} is the zero-emission commitment, and E_{Esfb} is an adjustment term for sources of unrepresented Earth system feedback (Rogelj *et al.*, 2019).

As described below, in this study we estimate carbon budgets directly from the ensembles of MESM simulations for different emission scenarios. Nevertheless, it is worth mentioning that the individual components of the above shown equation simulated by MESM are in a good agreement with the IPCC AR6 values. In particular, the median value of TCRE estimated from the 400-member ensemble of MESM simulations with 1% per year increase in CO_2 concentration (Sokolov *et al,* 2018) aligns well with the IPCC AR6 estimate (1.64°C/EgC in MESM vs 1.65°C/EgC in IPCC AR6). The IPCC AR6 estimates that the most likely value of ZEC for a time frame of half a century (50-years) is zero (0°C). This assessment is partially based on the results of the recent model inter-comparison study (MacDougall *et al.*, 2020), where multi-model mean is reported to be 0.06°C. The corresponding value simulated by MESM is 0.01°C. We also note that the mean value of historical temperature change (measured as a difference between 1850–1900 and 2010–2019) simulated by MESM, 1.07°C, is in a good agreement with the IPCC AR6 best estimate (see Figure 8).

At the same time, non-CO_2 warming simulated by MESM seems to be smaller than the assessed values by the IPCC AR6. According to AR6, median additional non-CO_2 warming at the time when global CO_2 emissions reach net zero is about 0.1°C–0.2°C relative to 2010–2019. For the *Sky 2050* scenario, median non-CO_2 warming in 2051 (i.e., the year when carbon emissions become zero), calculated as temperature difference between simulations with the *Sky 2050* scenario and simulations in which non-CO_2 emissions were fixed on their 2020 values, is only 0.03°C. In the IPCC AR6, the values for carbon budget calculation are also adjusted by 7GtC/°C for sources of unrepresented Earth system feedback mechanisms, such as permafrost thawing and others. While the changes in carbon emissions due to permafrost thawing are not taken into account in MESM, we include the changes in N2O and CH4 emissions from wetlands.

For our ensemble of simulations, we estimate the remaining carbon budget in the following way. Median peak temperature in the ensemble for the *Sky 2050* scenario equals to 1.67°C, meaning that under this scenario temperature will not exceed this value with 50% probability. The cumulative carbon emissions from year 2020 to year 2051 (when median temperature peaks) are 205 GtC (see Table A.1). Based on the values for 1.6°C and 1.7°C given in Table 5.8 of IPCC AR6 (IPCC, 2021), the remaining carbon budget for this level of warming is about 215 GtC (or 790 Gt CO_2). Similarly, median temperature in the *Archipelagos* scenario by the end of the simulation period stabilizes at 2.22°C (by 2094), with the carbon budget of about 500 GtC. As shown in **Table A.1**, the corresponding number from the IPCC AR6 report is about 470 GtC.

We also calculate the threshold exceedance budgets (TEB) that correspond to the amount of cumulative carbon emissions at the time a specific temperature threshold is exceeded, with a given probability. For the *Sky 2050* scenario, cumulative carbon emissions from 2020 to 2034 (i.e., the year when median temperature crosses 1.5°C) are 147 GtC. The cumulative emissions from 2020 to 2074 (i.e., the year when median temperature crosses back below 1.5°C) are almost the same (because of net carbon emissions being negative during 2051-2074), namely 152 GtC. This suggests that in a scenario for which emissions will be below this level, the 1.5°C threshold will not be exceeded. The IPCC AR6 estimate for the carbon budged required to stay below 1.5°C is 140 GtC. For the *Archipelagos* scenario, TEB for 1.5°C is somewhat higher, 156 GtC, and TEB for 2.0°C is 374 GtC, which is close to the IPCC AR6 estimate of 370 GtC.

The median temperature at the end of the century for the *Sky 2050* scenario is 1.24°C and at that point it continues to decrease rather than staying constant. The cumulative carbon budget for 2020-2100 in this scenario is about 60 GtC. IPCC Table 5.8 (IPCC, 2021) does not report the values lower than 1.3°C (from which the remaining budget is 40 Gt). Note that IPCC carbon budgets are subject to variations and uncertainties quantified in the columns on the right of the IPCC AR6 WGI Table 5.8. The overall values of carbon budgets for different warming levels calculated from MESM ensembles fell well into the range of uncertainty for the IPCC AR6 estimates.

Table A.1. Remaining carbon budget. The values for 1.5°C, 1.6°C, 1.7°C, 2.2°C, and 2.3°C warming since 1850-1900 are from Table 5.8 IPCC AR6 WGI (IPCC, 2021). They are subject to variations and uncertainties quantified in the columns on the right of IPCC Table 5.8 (for non-CO_2 scenario variation and geophysical uncertainties). For the *Sky 2050* scenario, two budgets are reported: threshold exceedance budget (TEB) and for median peak temperature.

	Warming since 1850-1900	**IPCC AR6 Remaining Carbon Budget from January 1, 2020**		**Carbon Budget from MESM**	
Scenario	**Degrees C**	**GtC**	**$GtCO_2$**	**GtC**	**$GtCO_2$**
Sky 2050 (for TEB)	1.5	140	500		
	1.5			150	550
Sky 2050 (at peak)	1.6	180	650		
	1.67	215	790	205	750
	1.7	230	850		
Archipelagos	2.2	460	1700		
	2.22	470	1725	500	1835
	2.3	510	1850		

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