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# Meeting the Goals of the Paris Agreement: Temperature Implications of the Shell Sky Scenario

Sergey Paltsev, Andrei Sokolov, Xiang Gao and Martin Haigh

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***—Ronald G. Prinn and John M. Reilly,***
*Joint Program Co-Directors*

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# Meeting the Goals of the Paris Agreement: Temperature Implications of the Shell Sky Scenario

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**Abstract:** The Paris Agreement makes long-term energy and climate projections particularly important because it calls for a goal that likely requires an energy system that is based on a radically different fuel mix than currently in use. This presents a challenge for energy companies as they try to anticipate the types of energy and fuels that will be required to stay competitive while meeting environmental requirements. A new scenario (called *Sky*) developed by Shell International examines the challenge of moving to an energy system with net-zero $CO_2$ emissions and gradually eliminate emissions from deforestation by midway through the second half of the century (specifically by the year of 2070). Using the MIT Integrated Global System Modeling (IGSM) framework, we simulate a 400-member ensemble, reflecting uncertainty in Earth system response of global temperature change associated with the Sky scenario by 2100. We find that for the median climate parameters the global surface temperature increase by 2100 is 1.75°C above the pre-industrial levels with an 85% probability of remaining below 2°C. The geographic distribution of the temperature change shows a stronger warming in Polar regions. If, in addition, there is a significant effort directed toward global reforestation then, with median climate parameters, temperature increase by 2100, is near 1.5°C above pre-industrial levels.



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## 1. Introduction

The Paris Agreement (UN, 2015) has established a global target 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 Agreement also calls for a peak in the global greenhouse gas (GHG) emissions as soon as possible and a balance between the anthropogenic emissions by sources and removal of GHGs by sinks in the second half of the century. There are numerous scenarios for GHG emission trajectories that are consistent with the climate stabilization at different levels. Many examples are included as part of the scenario assessment in the latest report of the UN Intergovernmental Panel on Climate Change (IPCC, 2014) that summarizes the results from the scientific literature from different modeling groups.

Fossil fuels are a primary source of human-induced GHG emissions and fossil fuel producers recognize the importance of energy-related emissions. For example, Shell has developed Mountains and Oceans scenarios (Shell, 2013) that aim to almost eliminate the global energy-related $CO_2$ emissions by 2100. The climate implications of the Mountains and Oceans scenarios are explored in Paltsev *et al.* (2016) and Monier *et al.* (2018), where they concluded that these scenarios exhibit a substantial movement toward temperature stabilization, resulting in increases of 2.4–2.7°C by 2100 relative to preindustrial levels. ExxonMobil in its recent energy outlook (ExxonMobil, 2018) included a section that provides an overview of potential pathways toward the 2°C climate goal, and the implications such pathways might have in terms of global energy intensity, carbon intensity of the world's energy mix and global demand for various energy sources. BP in its energy outlook to 2040 discussed two alternative $CO_2$ emission scenarios, called "faster transition" and "even faster transition", necessary to achieve the goals of the Paris Agreement (BP, 2018).

The objective of this paper is to provide an assessment of the temperature implications of the latest Shell scenario called "Sky" (Shell, 2018). In this study we apply the MIT Integrated Global System Modeling (IGSM) framework (Sokolov *et al.*, 2005, 2018) to assess the Sky scenario together with other scenarios of future low-carbon energy development and provide new insights on the changing global climate. The climate system component of the IGSM is the MIT Earth System Model (MESM), which couples a zonally-averaged model of atmospheric dynamics and chemistry, a thermodynamic sea-ice model, a land model with an ecosystem biogeochemistry model, and a mixed layer/anomaly diffusing model representing the processes of heat and carbon uptake in the ocean. Climate sensitivity, strength of aerosol forcing, and the rate of oceanic uptake of heat and carbon of the MESM can be varied by changing the strength of cloud feedback and the value of the ocean diffusion coefficient, allowing for analysis of uncertainty in global climate outcomes for a given anthropogenic emissions scenario.. The latest version of MESM is described in Sokolov *et al* (2018).

This paper is organized in the following way. In Section 2 we describe the global energy-related $CO_2$ emissions from the Sky scenario developed by Shell and explore the emission profiles of other greenhouse gases and non-energy $CO_2$. We also provide the corresponding values from Mountains and Oceans scenarios as references. Section 3 reports the impacts of the emissions on global average surface temperature, while in Section 4 we show the geographic distribution of the temperature changes. Section 5 provides a sensitivity analysis with respect to different assumptions about land use change (LUC) emission. Section 6 concludes.

## 2. Anthropogenic GHG Emissions

The Sky scenario envisions a rapid energy transition to the low-carbon sources (Shell, 2018). The Sky scenario includes the current energy demand growth in the emerging economies and a steady strengthening of the pledges that countries made under the Paris Agreement process up to 2025–2030. From 2030 the scenario assumes a target-driven approach that results in substantial electrification of energy use and scaling up of low-carbon technologies, like wind and solar. Hydrocarbons continue to play a role in some sectors like heavy-industry processes and heavy-duty transport. Methane emissions from oil and natural gas industry are substantially reduced by following best practices to mitigate them. In the later part of the century, carbon capture and storage (CCS) technology is widely employed both on fossil fuels and bioenergy.

The resulting energy-related $CO_2$ emissions are provided in **Figure 1** (reported here at 10-year intervals). The figure also shows the emission profiles for other sources of anthropogenic GHGs, developed separately from the Shell Sky scenario described in Shell (2018). The profiles are developed with an input from the experts from Shell. Alternative land-use $CO_2$ emission profiles are developed based on consultations with The Nature Conservancy (Griscom *et al.*, 2017). Mitigation of GHGs is driven by our estimates of their marginal abatement costs based on our assessments from the MIT Economic Projection and Policy Analysis (EPPA) model (Morris *et al.*, 2012; Paltsev *et al.*, 2015), on the analysis by the US Environmental Protection Agency for non-$CO_2$ GHGs (EPA, 2014), and on the exploration by the International Energy Agency for methane emissions related to fossil fuels (IEA, 2017). We have based the GHG emission trajectories on our previous analysis of the scenarios consistent with 2°C stabilization (Paltsev *et al.*, 2016; Sokolov *et al.*, 2017a).

Global energy-related $CO_2$ emissions have grown from about 24 gigatonnes (Gt) in 2000 to about 34 Gt in 2015.

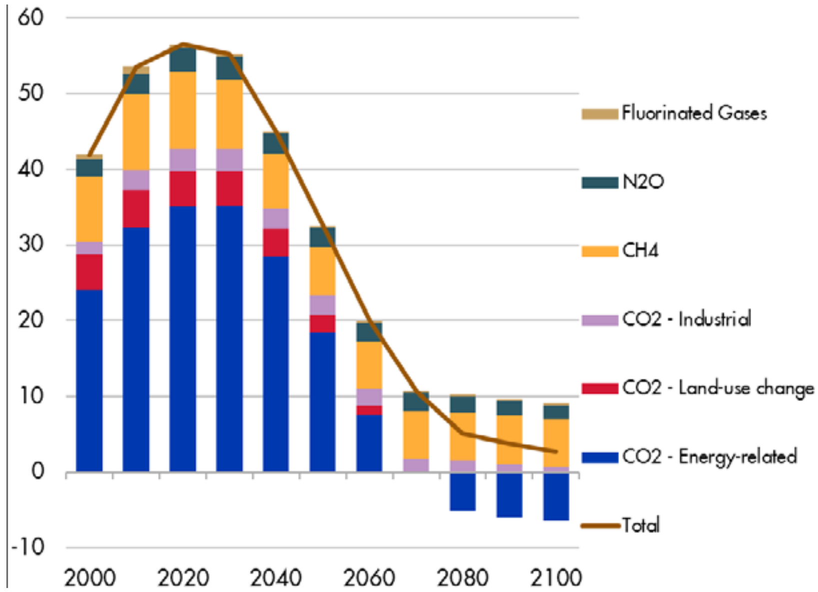


**Figure 1.** Contribution of different anthropogenic GHGs to the global total GHG emissions ($GtCO_2e$/year) in the Sky scenario.

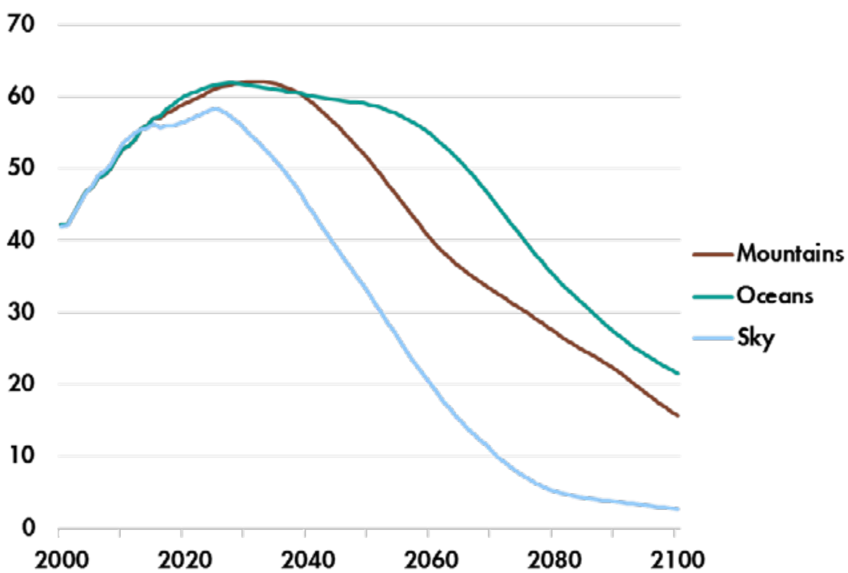


**Figure 2.** World total anthropogenic GHG emissions ($GtCO_2e$/year).

The emissions in the Sky scenario are projected to grow further to about 36.5 Gt in 2025–2026 and then they start to decline. The rate of decline accelerates after 2030 and the decline rate in 2035–2070 (-0.9 Gt/year) exceeds the rate of increase in energy-related $CO_2$ emissions in 2000–2015 (+0.7 Gt/year).

**Figure 2** depicts the global GHG emissions in $CO_2$-equivalence ($CO_2e$) applying Global Warming Potential (GWP) indices to non-$CO_2$ gases based the values from the IPCC Fifth Assessment Report (AR5) (Myhre *et al.*, 2013). For comparison, we provide the profiles of the Mountains and Oceans scenarios from the 2013 Shell analysis (Shell, 2013). The ambition for a rate of GHG emission reduction in the Sky scenario is increased in comparison to the profiles in the Mountains and Oceans scenarios. While energy-related $CO_2$ emissions in the Sky scenario become net-zero in 2070 and then negative after that (due to deployment of a negative emission technology like bioenergy with CCS), the total anthropogenic GHG emissions stay positive throughout the 21$^{st}$ century due largely to the challenges of reducing methane from livestock and rice production and nitrous oxide from soils, as well as continuing emissions of some of the fluorinated gases and industrial emissions of $CO_2$.

The profiles for the global methane ($CH_4$) emissions are provided in **Figure 3**. In the Sky scenario methane related to oil and natural gas production is reduced by 2050 to

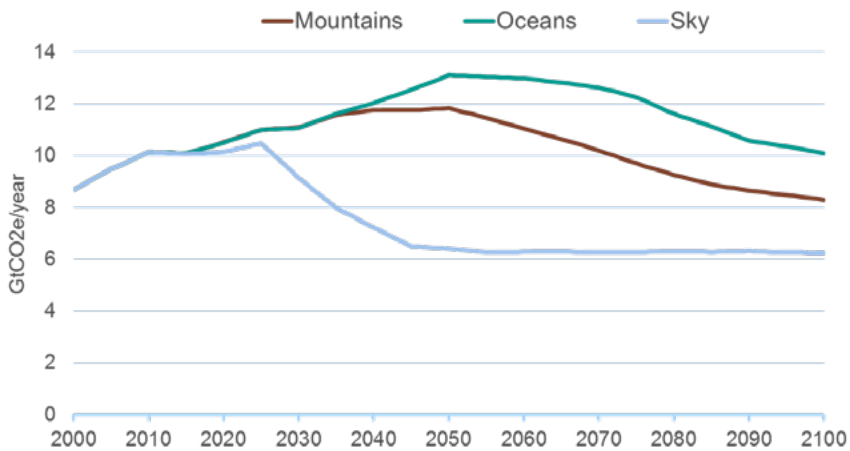


**Figure 3.** World methane ($CH_4$) emissions ($GtCO_2e$/year).

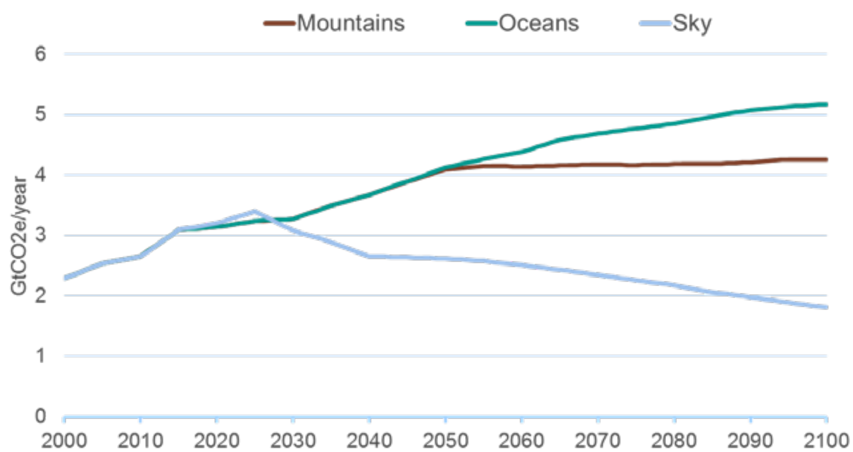


**Figure 4.** World nitrous oxide ($N_2O$) emissions ($GtCO_2e$/year).

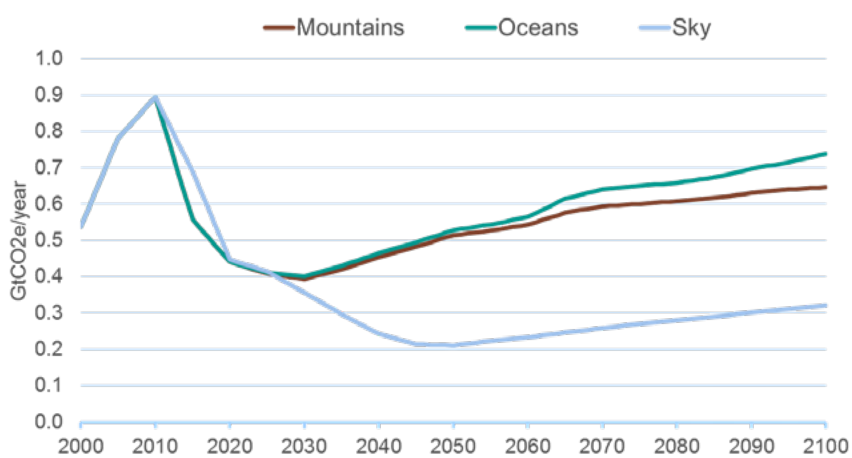


**Figure 5.** Total global emissions of F-Gases (PFCs, HFCs, $SF_6$) (Gt $CO_2e$/year).

the levels consistent with the best practices (IEA, 2017). Methane emissions after 2050 are dominated by agriculture and landfill related activities. Nitrous oxide ($N_2O$) emissions are shown in **Figure 4**. They are dominated by agriculture related emissions. **Figure 5** depicts the emissions of F-gases. They include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6). While the IGSM tracks the F-gases separately, here we combine and convert them into $CO_2$-equivalence for reporting purposes. Fluorinated gases are used inside the products like refrigerators, air-conditioners, foams and aerosol cans. Emissions from these products are caused by gas leakage during the manufacturing process as well as throughout the products' life. Fluorinated gases are also used for producing metals and semiconductors. We project a substantial reduction in F-gases emissions up to 2050 and a slight increase afterwards driven by HFCs used in air conditioning and refrigeration.

For land use change-induced $CO_2$ emissions, we take the historic (2000–2015) data from The Global Carbon Budget Project (Le Quere *et al.*, 2016) and then assume a reduction in deforestation and an increase in reforestation that drive these emissions to zero by 2070 in the Sky scenario. In contrast, in the Mountains and Oceans scenario, zero land use emissions are achieved only by 2100. The assumed profiles are reported in **Figure 6**.

Process-related industrial $CO_2$ emissions are provided in **Figure 7**. These emissions are mostly driven by cement, iron and steel and petrochemical production. The assumed reductions in industrial $CO_2$ emissions are related to an introduction of carbon capture and storage technologies and increased efficiencies.

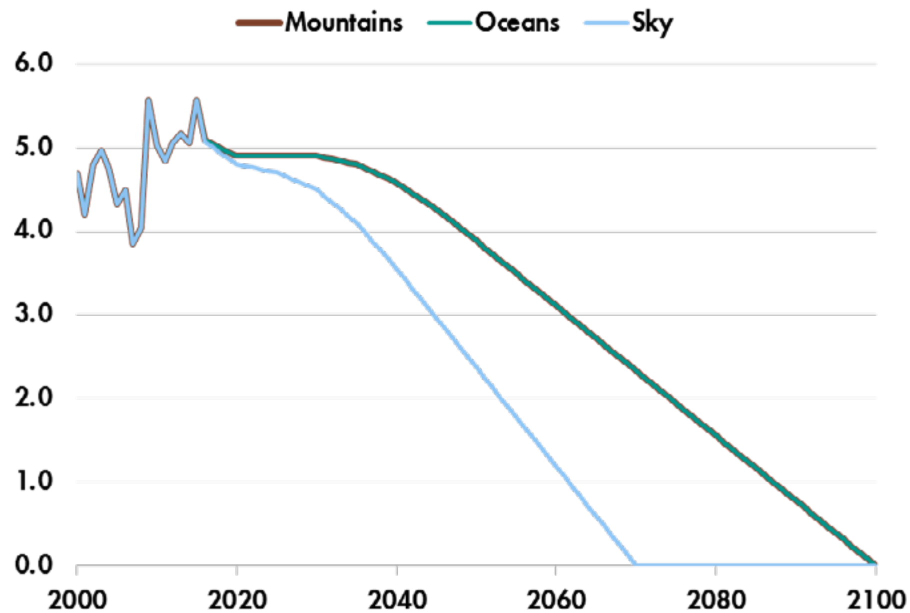


**Figure 6.** World land-use change $CO_2$ emissions (Gt $CO_2$/year).

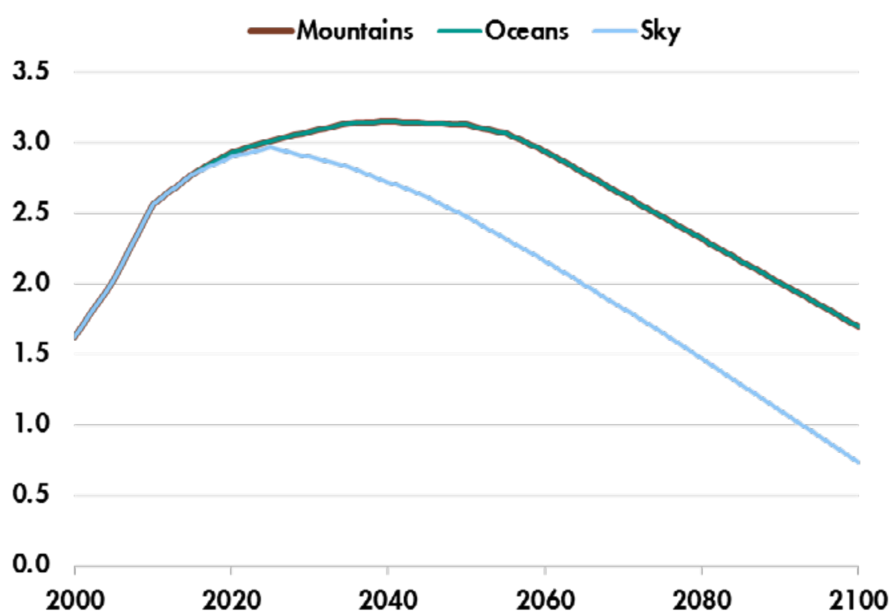


**Figure 7.** World industrial $CO_2$ emissions (Gt $CO_2$/year).

## 3. Temperature Increase in the Sky Scenario

To evaluate climate impacts of the GHG emission trajectories described in the previous section, we generated a 400-ensemble run of the Sky scenario. The 400 samples are chosen from a probability distribution of climate parameters as described in Libardoni (2017) and Sokolov *et al* (2017b, 2018). 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 greenhouse gases emissions from the Sky scenario. For comparison, we also carried out ensembles for the Mountains and Oceans scenarios.

For the median values of the climate parameters, the Sky scenario leads to global average surface temperature stabilization at around 1.75°C by 2100 above the preindustrial level. As shown in **Figure 8**, in contrast to the Oceans and Mountains scenarios, the Sky scenario achieves the long-term goal of the Paris Agreement to keep the temperature increase "well-below" 2°C. Figure 8 also shows the observed historic temperature increase and the IGSM model realization for the historic period. The dots on the figure represent annual temperature results, while the heavy lines show 5-year averages.

**Figure 9** provides the results for the surface temperature increase for 400 runs of the Sky scenario with different values of climate parameters. The 90% probability range for the Sky scenario is between 1.39°C and 2.15°C.

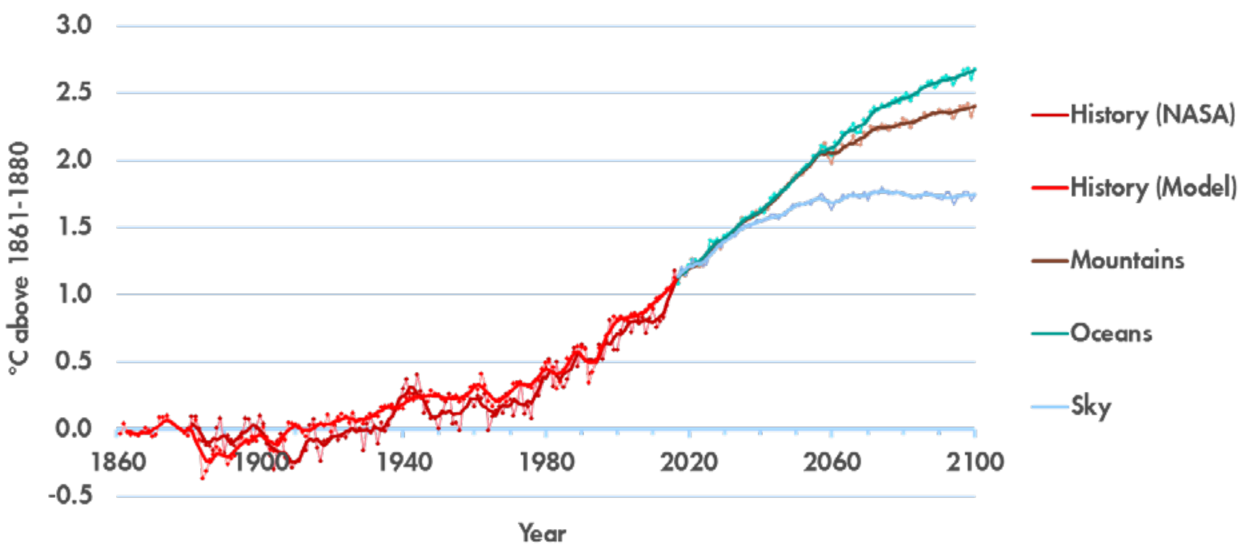


**Figure 8.** Global average surface air temperature change relative to the preindustrial level of 1861–1880 (C°).

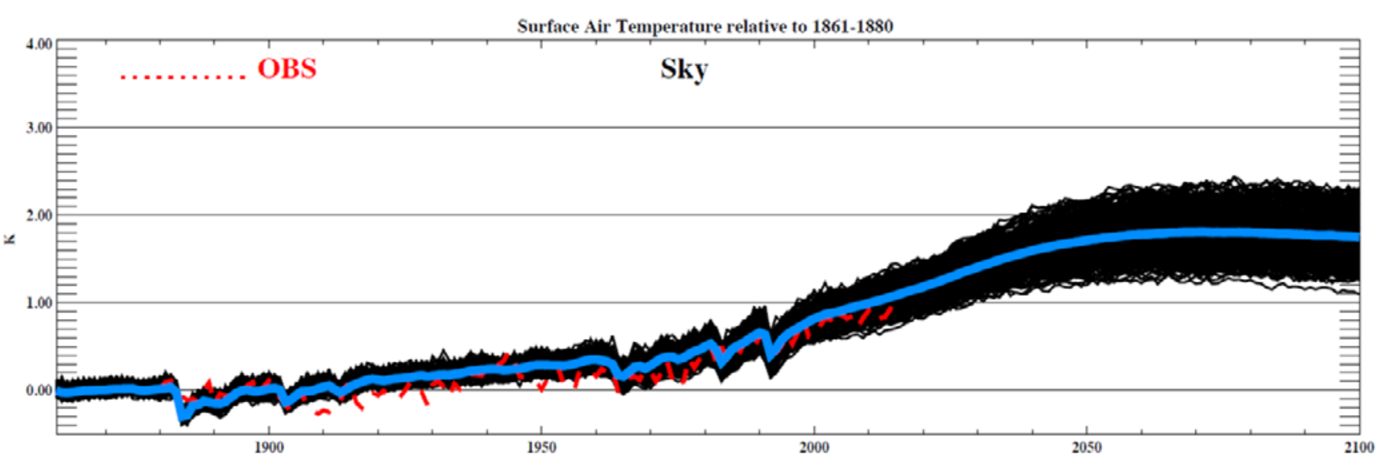


**Figure 9.** 400-runs ensemble results for global average surface air temperature change relative to the preindustrial level of 1861–1880 (C°). Blue line represents the mean of the ensemble.

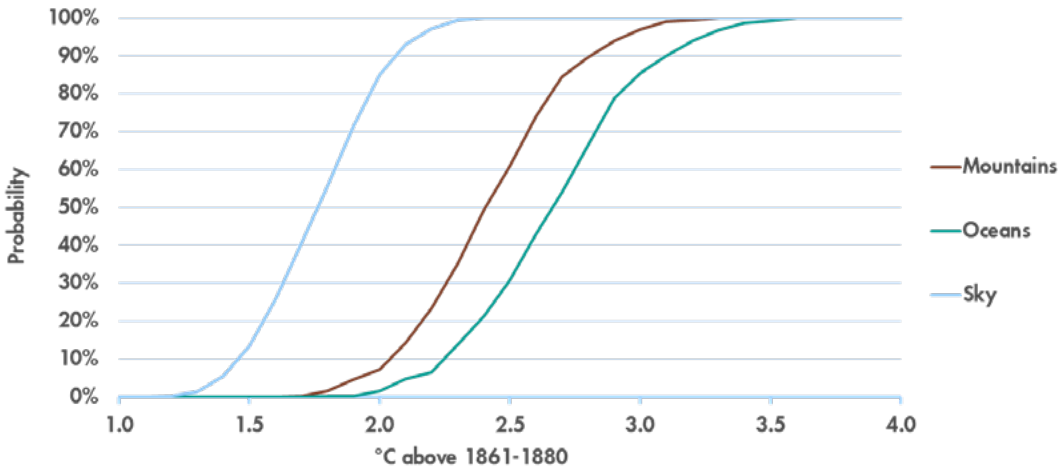


**Figure 10.** Probability (%) that surface air temperature remains below given values in the last decade of the 21st Century.

**Figure 10** shows the cumulative probability density and it provides another way of illustrating the likelihood of reaching various temperature increases relative to preindustrial levels. As seen in the figure, the Sky scenario has an 85% probability of remaining below 2°C, 50% probability of remaining below 1.75°C, and 13% probability of remaining below 1.5°C in the last decade of the 21st century relative to the 1861–1980 mean. The probabilities of staying below 2°C are substantially lower for the Mountains and Oceans scenarios. They are 7% and 1.5%, correspondingly.

## 4. Geographic Distribution of the Temperature Increase

The version of the MESM model used to produce the large ensemble projections is a 2-dimensional atmosphere-ocean general circulation model, resolving the climate system vertically and by latitude. We used a statistical downscaling approach (Schlosser *et al.*, 2013) to simulate temperature change across longitude based on the IGSM zonal surface air temperature simulations. The climatology of transformation coefficients under contemporary condition is derived from Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker *et al.* 2011) dataset. Pattern shifts in response to human-forced change are obtained from Phase 5 of the Coupled Model Intercomparison Project (CMIP5, Taylor *et al.* 2012) 1pct$CO_2$ climate model simulations in which atmospheric $CO_2$ increases at an idealized rate of 1% per year to quadrupling. As such, we can consider the uncertainty in regional climate change characterized by each of 33 CMIP5 participating climate models. We employ a 400-member ensemble of IGSM projections, complemented with 33 CMIP5 climate model patterns to develop a 13,200-member ensemble of climate change projections for the Sky scenario. **Figure 11** show the distribution of changes in temperature relative to1861–1880 averaged across the 13,200-member ensemble. Over the majority of land area, the temperature increases by around 2°C. However, Europe shows a lower increase, while Polar regions experience a higher increase in temperature.

**Figure 12** illustrates the geographic distribution of temperature increases in the Mountains and Oceans scenarios. In this figure, most of the land mass is colored in green, which represents an increase of more than 3°C. Some parts of the Northern regions are colored in red, which represents an increase of more than 6°C. While the global average temperatures in the Sky, Mountains and Oceans scenarios do not seem dramatically different – they are 1.75°C, 2.4°C, and 2.7°C, respectively – the resulting temperature increases in some parts of the world are quite alarming in the Mountains and Oceans scenarios.

## 5. Land-Use $CO_2$: Nature-Based Solutions

**Figure 13** depicts different assumptions about the land-use $CO_2$ emissions. The Mountains and Oceans scenarios assume the same land-use emission profiles. For the Sky scenario, we created three additional land-use $CO_2$ emission profiles. Two of these, based on the estimates from Reilly *et al.* (2012) and Griscom *et al.* (2017), consider enhanced use of land for carbon mitigation. These two scenarios with nature-based solutions (NBS) involve reforestation, reduced deforestation, better forest management, and other land related activities (see Griscom *et al,* 2017, for more details about the activities and their potential for improved land management actions). We call these scenarios as *Sky+Restoration NBS* and *Sky+Extra NBS*. We assume a wide deployment of land management practices after 2030 and a gradual exhaustion of new options by the end of the century. A third scenario, called *Sky without NBS*, keeps land-use emissions at a current (2015) level (this scenario is not shown in Figure 13).

**Figure 14** represents the temperature impacts of these different land-use change emissions profiles. For the median

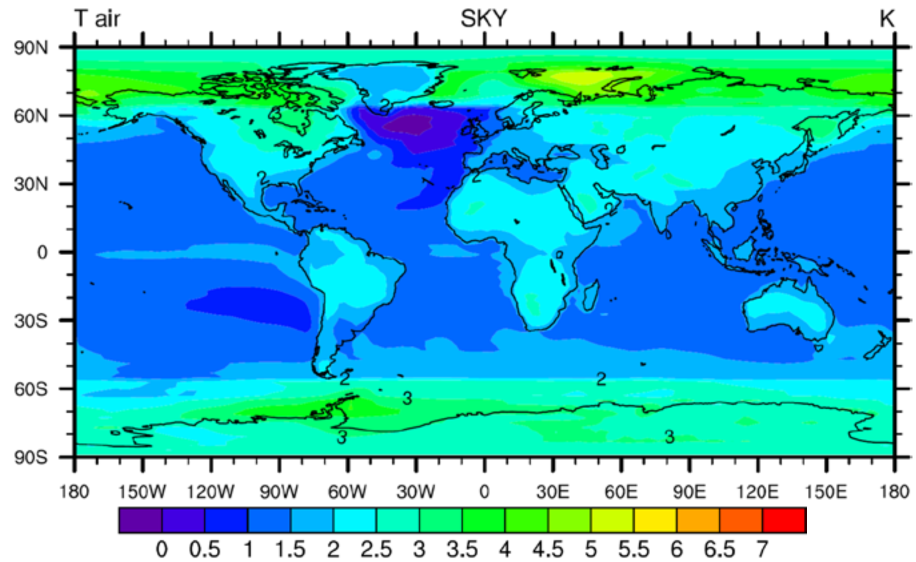


**Figure 11.** Geographic distribution of surface temperature change in the Sky scenario

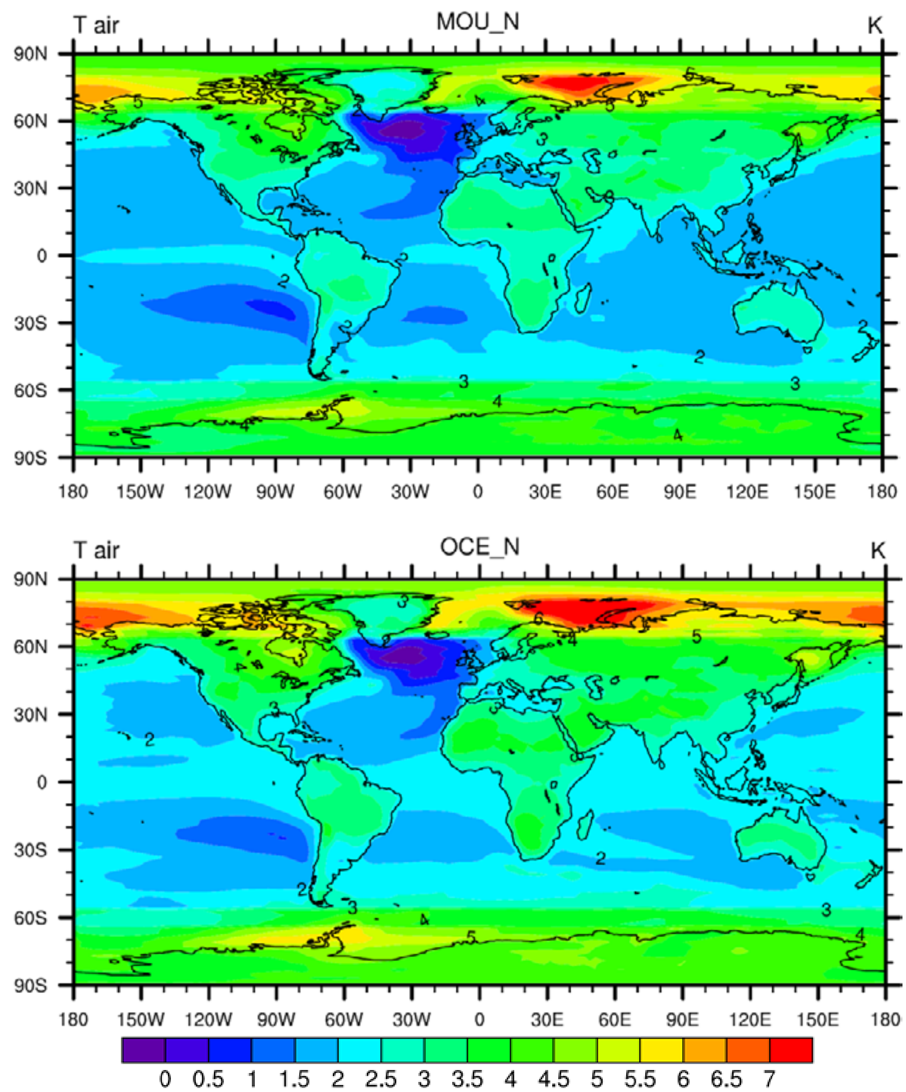


**Figure 12.** Surface temperature change in the Mountains (top panel) and Oceans (bottom panel) scenarios

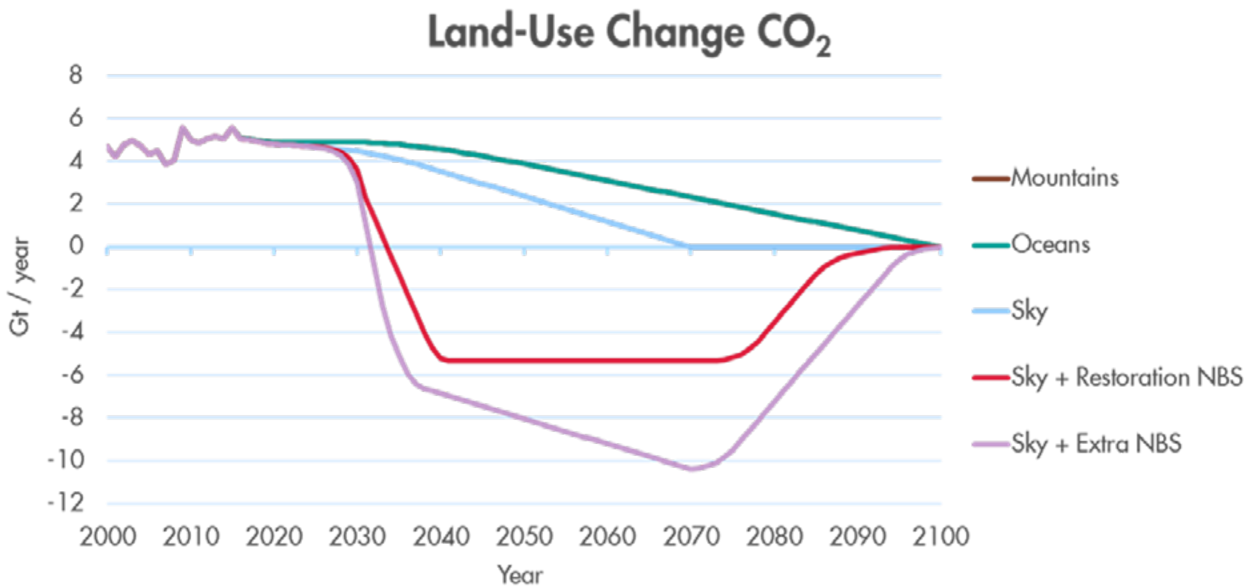


**Figure 13.** Alternative assumptions for the land-use $CO_2$ emissions in the Sky scenario ($GtCO_2$/year)

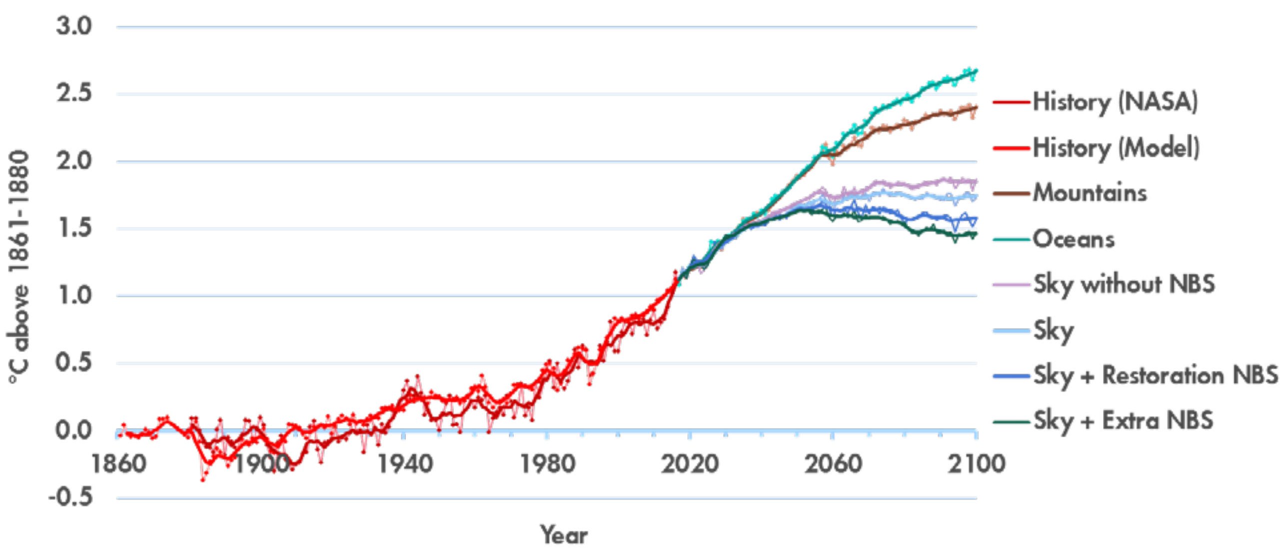


**Figure 14.** Temperature change in the scenarios with alternative assumptions for the land-use $CO_2$ emissions

values of the climate parameters, all four variants of the Sky scenario (*Sky*, *Sky without NBS*, *Sky+Restoration NBS*, *Sky+Extra NBS*) are below 2°C. Additional NBS actions reduce the surface temperature increase and the *Sky+Extra NBS* scenario is approaching 1.5°C above the pre-industrial levels by 2100.

## 6. Conclusions

The Paris Agreement makes long-term energy and climate projections particularly important because it calls for a goal that likely requires an energy system that is based on a radically different fuel mix than currently in use. This presents a challenge for energy companies as they try to anticipate the types of energy and fuels that will be required to stay competitive while meeting environmental requirements. In order to achieve the low-carbon energy mix, the energy companies will need to reduce GHG emissions not only in their operations, but also in their products. Many energy experts (IEA, 2017), including those at the leading energy companies (BP, 2018; ExxonMobil, 2018) have developed energy scenarios aimed toward decarbonization of the energy system. The Sky Scenario, developed by the Shell Scenarios Team, is the first Shell scenario that has a net-zero energy-related $CO_2$ emissions in the 21st century (specifically by 2070).

Using the MIT Integrated Global System Modeling (IGSM) framework, we assess the global temperature changes up to 2100 associated with the Sky scenario. The global surface temperature increase in the Sky scenario in 2100 is 1.75°C above the pre-industrial levels. Based on a 400-ensemble member IGSM runs, we find that in the last decade of the 21st century the global surface temperature increase in the Sky scenario has an 85% probability of remaining below 2°C. Geographic distribution of the temperature change shows a stronger warming in Polar regions. A significant additional contribution from global reforestation efforts would lead to a trajectory of a lower temperature increase in 2100, approaching 1.5°C above the pre-industrial levels.

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