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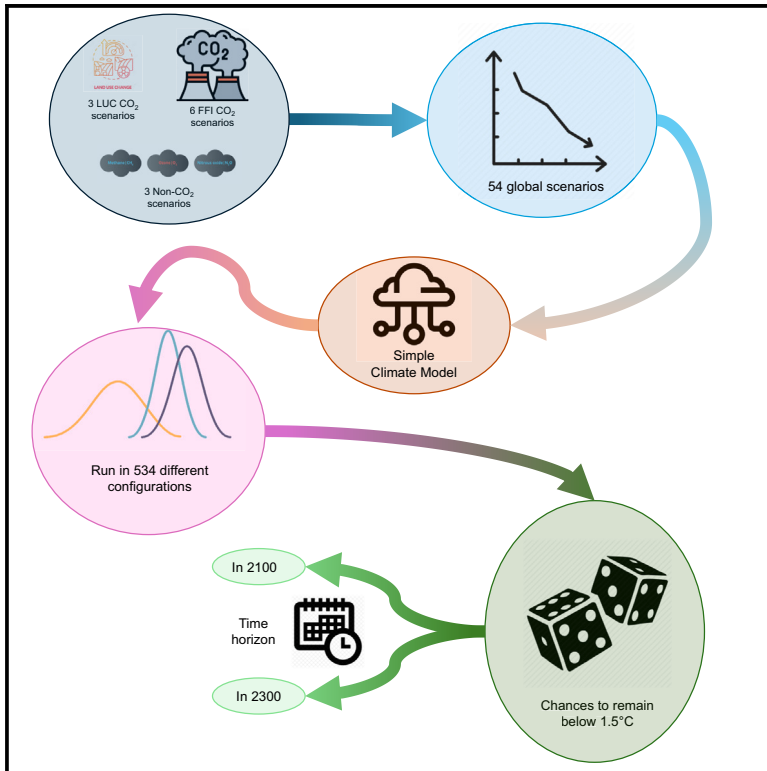
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# On the chances of staying below the 1.5°C warming target

## Graphical abstract



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## In brief

Cutting fossil fuel emissions by 5% annually may only give a 50% chance of staying below 1.5°C warming by 2100. This study uses the latest data on fossil and land-use CO<sub>2</sub> emissions, extends the view to 2300, and thus highlights the need for both deep emission cuts and CO<sub>2</sub> removal strategies for long-term climate goals. Mitigation of land-use CO<sub>2</sub> and non-CO<sub>2</sub> greenhouse gases is also shown to play a critical role.

## Highlights

- >5% annual fossil CO<sub>2</sub> emissions cut needed for only 50% chance to stay below 1.5°C
- Chance drops to 30% if time horizon is 2300 instead of 2100
- Pessimistic non-CO<sub>2</sub> and land-use CO<sub>2</sub> scenarios lower these to 23% and 41%, respectively
- Optimistic ones raise them to 66% and 61%, confirming key role of non-CO<sub>2</sub> and land-use CO<sub>2</sub> scenarios

## Article

# On the chances of staying below the 1.5°C warming target

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**SCIENCE FOR SOCIETY** We used an observation-informed numerical model that differs from the traditional “carbon budget” approach to estimate fossil CO<sub>2</sub> emissions cuts in line with limiting global warming, considering the latest data on emissions up to 2022. We showed that to have a 50% chance of staying below 1.5°C this century, emissions from fossil fuel burning and industrial processes must drop by about 5% each year (or equivalently, reach zero in 20 years). If we extend the timeframe to 2300, the chances drop to 30% even with this level of emissions reduction. The success of limiting warming also depends heavily on future land use (especially deforestation) and reducing other greenhouse gases besides CO<sub>2</sub>. This research highlights the importance of taking stronger action now to reduce emissions and finding ways to remove CO<sub>2</sub> from the atmosphere. It also emphasizes the need for smart land-use practices and tackling other greenhouse gases to achieve our climate goals.

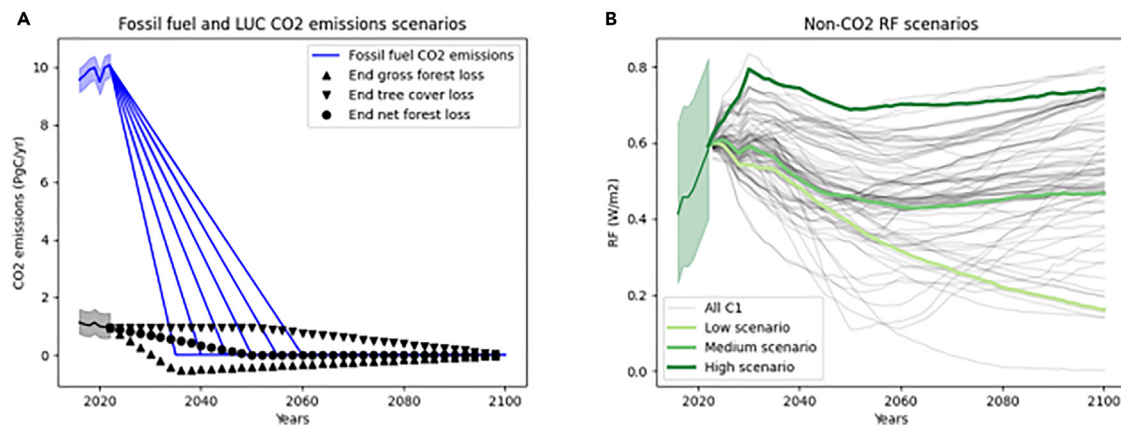
## SUMMARY

Pledges at recent climate summits fall short for 1.5°C warming. Here, we calculate the CO<sub>2</sub> emissions reduction required to stay below 1.5°C, considering available data on current emissions up to 2022, extending the time horizon to 2300, and using an approach different from the carbon budget to offer another perspective on what is required to stay below 1.5°C. For a 50% chance of staying below 1.5°C during this century, fossil fuel and industry CO<sub>2</sub> emissions need to decrease linearly by about 5% per year, in line with other recent studies. However, extending the time horizon to 2300 leads to chances dropping to 30% for the same decarbonization scenario without sustained carbon dioxide removal beyond levels needed for offsetting residual CO<sub>2</sub> emissions. We further show that the chances of staying below 1.5°C of global warming critically hinge on the assumed future land-use CO<sub>2</sub> emissions and mitigation of non-CO<sub>2</sub> forcers.

## INTRODUCTION

At COP28 in Dubai, the parties reaffirmed their ambition to limit climate change to a temperature target of 1.5°C above pre-industrial levels. Given the world's emissions trajectory in recent years,<sup>1–3</sup> meeting this target without overshoot seems very ambitious at best, and virtually impossible at worst. Global warming has already reached 1.15 °C above pre-industrial levels over the 2013–2022 period,<sup>4,5</sup> and the 1.5°C limit has recently been surpassed for a year-long period.<sup>6,7</sup> The latest Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6)<sup>8</sup> gave an estimate of the remaining carbon budget (RCB; that is, the total amount of allowable anthropogenic CO<sub>2</sub> emissions) of 500 GtCO<sub>2</sub> from January 2020 for a 50% chance of

staying below 1.5°C.<sup>9</sup> This was recently updated<sup>2</sup> to 380 GtCO<sub>2</sub> from January 2023, given current annual emissions of ~40 GtCO<sub>2</sub> per year.<sup>10</sup> Another study using an updated methodology<sup>11</sup> gave a reduced estimate of 300 GtCO<sub>2</sub> from January 2022. A new synthetic effort further reduced the estimate to 250 GtCO<sub>2</sub> from January 2023,<sup>4</sup> just half of the initial AR6 estimate. One of the sources of uncertainty in RCB estimates is the assumed level of non-CO<sub>2</sub> emissions. More emissions of non-CO<sub>2</sub> species like methane and black carbon will warm the climate and imply a reduced RCB. An aggressive and early abatement of methane and black carbon emissions would thus advance the timing of peak warming and reduce its magnitude.<sup>12</sup> On the other hand, reductions in SO<sub>2</sub> emissions, precursors of sulfate aerosols, would cause additional warming in the short



**Figure 1. Fossil fuel, land use, and non-CO<sub>2</sub> scenarios**

(A and B) CO<sub>2</sub> emissions from FFI and land use (A) and non-CO<sub>2</sub> RF (B) scenarios used in this study. Shaded areas around historical pathways indicate the 1-sigma uncertainty range. As historical pathways are different in every configuration of the model due to physical uncertainty, the starting point of our projection scenarios differs depending on the configuration. Here, bold lines for both historical and projections show the median value given by Pathfinder.

term<sup>13</sup> as their present-day contribution to radiative forcing (RF) is negative and the lifetime of sulfate aerosols is only a few months at most.<sup>14</sup> Here, we integrate the latest available data on temperature,<sup>15</sup> CO<sub>2</sub> concentration,<sup>16</sup> fossil fuel and industry (FFI) CO<sub>2</sub> emissions, land-use change (LUC) emissions<sup>10</sup> (which were not always well documented in previous RCB studies), and non-CO<sub>2</sub> RF<sup>17</sup> with the Pathfinder model to calculate what it takes to remain below 1.5°C. Pathfinder is a reduced-complexity climate and carbon-cycle model, calibrated on observations and climate projections from AR6.<sup>10</sup> By differentiating between FFI and LUC emissions, and by examining non-CO<sub>2</sub> RF scenarios corresponding to the range of ambitious mitigation scenarios in AR6, we shed light on the importance of these factors in determining the likelihood of staying below the 1.5°C target.

To estimate the level of effort needed to remain below 1.5°C, we created stylized mitigation scenarios (Figure 1). We consider FFI and LUC CO<sub>2</sub> emissions separately, as they have different dynamics and drivers. For FFI CO<sub>2</sub> emissions, we assume a linear rate of decrease starting from 2022 and reaching zero in 6 different years in the future (every 5 years from 2035 to 2060). As an extension of the analysis, we also investigate a scenario with net-zero reached in 2100 to estimate its chances to remain below 2°C. For LUC emissions, we apply three interpretations of the Glasgow pledge on deforestation<sup>18</sup>: a pessimistic one with constant emissions until 2050, a mid-range one with a linear decrease of LUC emissions down to zero in 2050, and an optimistic one that leads to a peak of negative CO<sub>2</sub> emissions in 2035; in all interpretations, LUC emissions then go back to zero in 2100. We also use three contrasted scenarios of non-CO<sub>2</sub> RF within the most ambitious category of scenarios assessed in the latest IPCC report<sup>19,20</sup> (C1 category). Finally, we simulate global temperature change until 2100, a commonly accepted time frame of the Paris Agreement, and further until 2300 to analyze longer-term dynamics. We then run the simulations in 534 different parameter configurations to estimate chances of remaining below 1.5°C or 2°C without overshoot, while accounting for physical uncertainty (see [experimental procedures](#)).

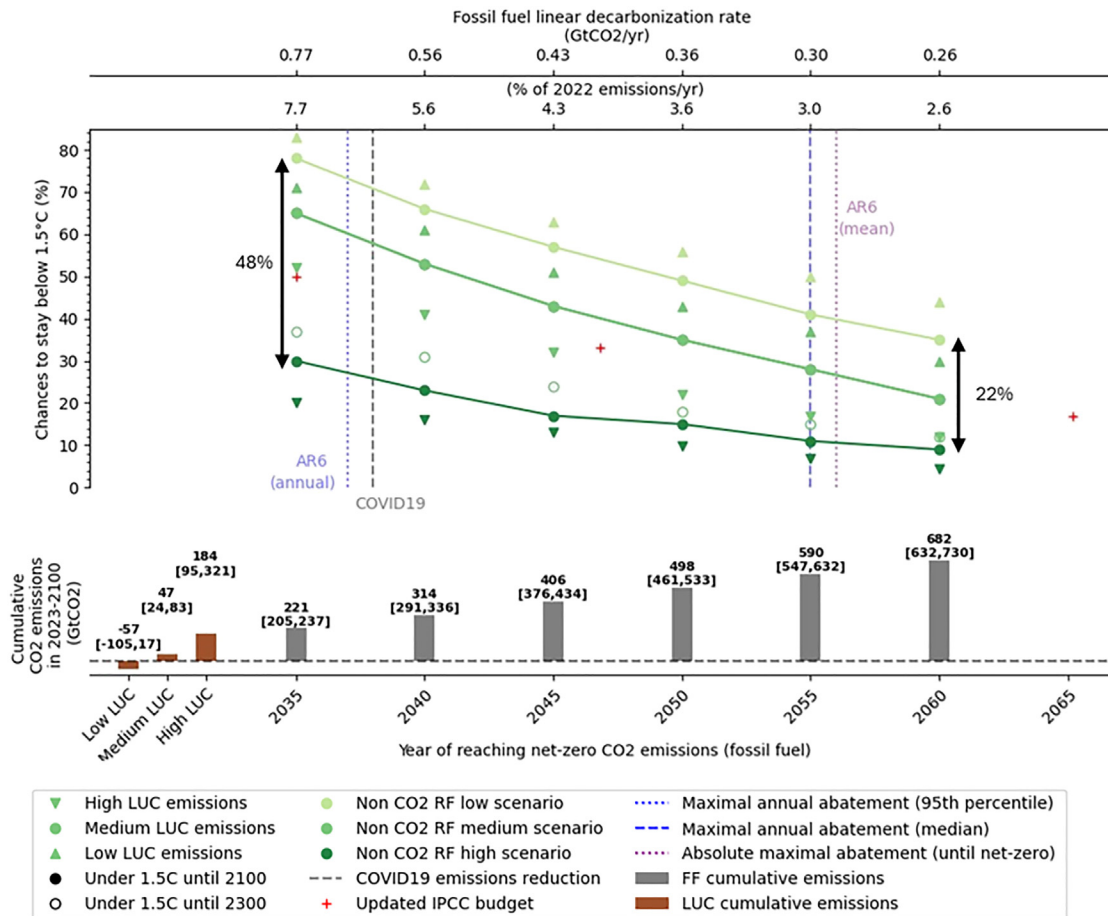
## RESULTS

### Chances of staying below 1.5°C until 2100

Figure 2 shows that staying below 1.5°C is not fully guaranteed in any of our mitigation scenarios. Even net-zero FFI CO<sub>2</sub> emissions in 2035, achievable with a very high decarbonization rate of 7.7% of 2022 emissions per year, and the most optimistic non-CO<sub>2</sub> and LUC assumptions, offer only an 83% chance of meeting the target. If we take a scenario with intermediate assumptions on non-CO<sub>2</sub> and LUC, a decarbonization rate of 5.6% year<sup>-1</sup> (i.e., net-zero FFI CO<sub>2</sub> emissions in 2040) is still required to get a 53% chance of staying below 1.5°C. This decarbonization rate is comparable with the temporary 6.3% reduction observed in 2020 during the COVID-19 pandemic,<sup>21</sup> when human activities were severely constrained; however, this level of decarbonization would need to be achieved every single year. This decarbonization rate is also higher than what is simulated in any integrated assessment model (IAM) scenario, as the earliest CO<sub>2</sub> FFI net-zero across all AR6 database is in 2056 (pink line on Figure 2). Moreover, most IAMs do not consider such a decarbonization rate over a 5-year period (blue lines on Figure 2), raising questions as to its technological feasibility.

Our results also show that the choice of the non-CO<sub>2</sub> scenario has a larger impact on the exceedance probability than the LUC scenario, with a maximal spread of 48 and 22 percentage points, respectively (Figure 2). This result is consistent with the large uncertainty in future warming due to non-CO<sub>2</sub> reported earlier.<sup>22</sup>

In comparison, IAMs suggest more modest decarbonization rates in their most ambitious scenario categories. The highest projected average rate of reduction of FFI CO<sub>2</sub> emissions is 2.9% per year, translating to net-zero in 2056. Such a scenario would have less than a 50% chance to remain below 1.5°C under the most optimistic LUC and non-CO<sub>2</sub> RF scenarios and an approximately 30% chance under the medium LUC and non-CO<sub>2</sub> RF scenarios according to our model. However, these AR6 scenarios start in 2015, assuming either an immediate decline in FFI CO<sub>2</sub> emissions or emission plateauing until 2020



**Figure 2. Chances of staying below 1.5°C following various mitigation scenarios for FFI and LUC CO<sub>2</sub> emissions and non-CO<sub>2</sub> RF**

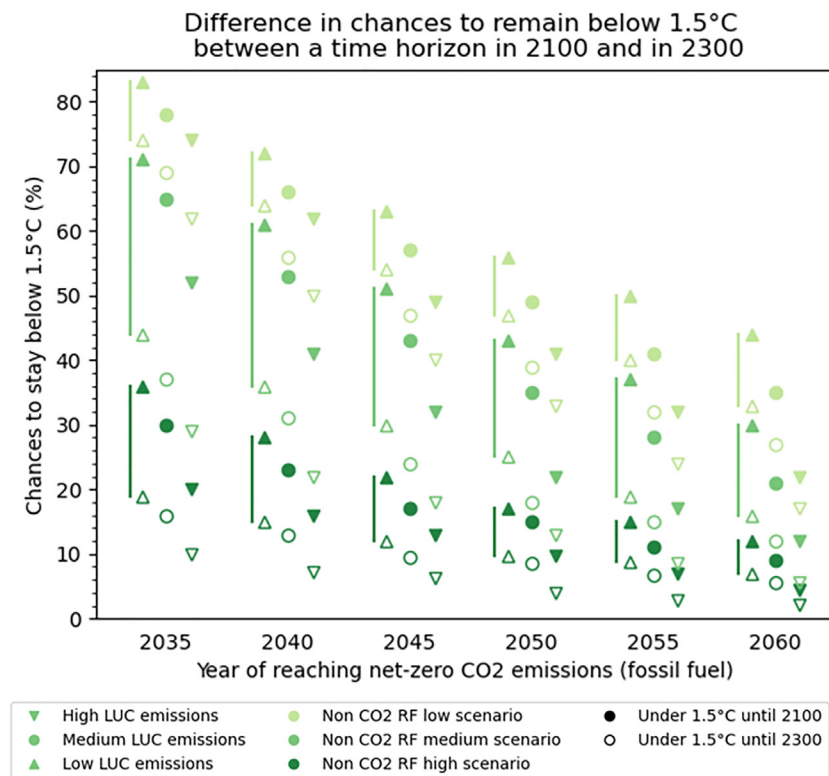
FFI CO<sub>2</sub> emissions are assumed to decrease linearly to zero in 2035, 2040, 2045, 2050, 2055, or 2060. The colors distinguish the scenarios for non-CO<sub>2</sub> RF, marker shapes differentiate scenarios for CO<sub>2</sub> LUC emissions, while filled and open markers differentiate the time horizon considered for the 1.5°C target (respectively, 2100 and 2300). To keep the figure readable, the low LUC/high non-CO<sub>2</sub> and high LUC/low non-CO<sub>2</sub> combinations are not shown and the open circle for the 2300 likelihood is only given for the central case (medium LUC and RF). Figure 3 displays all combinations and 2300 likelihood with error bars to highlight the likelihood difference. The red crosses are the updated IPCC budgets estimated by Lamboll et al.<sup>11</sup> from which our central LUC CO<sub>2</sub> emissions was subtracted. The gray dashed line indicates the level of the short-term drop in FFI CO<sub>2</sub> emissions caused by the COVID pandemic.<sup>21</sup> The blue lines indicate the level of the maximal annual abatement found in AR6 scenarios. By maximal annual abatement, we measure the largest yearly reductions (mean across a 5-year period) found in the IPCC’s AR6 database. We display the 95<sup>th</sup> percentile (or the 5<sup>th</sup> percentile of most ambitious yearly reduction), which we designate by the “maximal annual abatement (95<sup>th</sup> percentile)” and the median, explicitly named as the “maximal annual abatement (median).” The pink line (“absolute maximal abatement”) indicates the earliest date for FFI net-zero emissions in AR6 scenarios. See [experimental procedures](#) for more details on the significance of the blue and pink lines. Bar plots show the associated budget for FFI emissions (gray bars) and the LUC emissions scenarios (brown bars). The 90% uncertainty range is shown in the brackets.

before stringent mitigation, thus not accounting for the historical increase in emissions up to 2022 and explaining the lower decarbonization rate in IAMs.

It is also important to look at the maximum annual abatement to determine what the IAMs consider technologically feasible over a short period of time. The median of the maximum annual abatement across all scenarios from the AR6 database (blue dashed line in Figure 2) would result in reaching net-zero in 2055, which is too late to have more than a 60% chance of staying below 1.5°C. The 95<sup>th</sup> percentile (blue dotted line in Figure 2) of the maximum annual abatement is equal to 6.6% of 2022 emissions per year, which would lead to net-zero in 2037. To keep more than a 50% chance to remain below 1.5°C, decar-

bonization rates from the upper range of the IAM’s maximum annual rates must be maintained until net-zero.

The RCB presented in the latest IPCC report is a synthesis whose various elements are derived from diverse scenarios, models, and assumptions that are not necessarily consistent with one another.<sup>4,11</sup> For instance, the non-CO<sub>2</sub> warming for a given global temperature in the RCB is based on climate projections of realistic scenarios made with a simple climate model, while the TCRES (transient climate response to cumulative emissions) used to estimate the CO<sub>2</sub> budget is derived from an idealized experiment simulated by complex Earth system models. In contrast, our approach selectively presents scenarios under an internally consistent set of assumptions,



**Figure 3. Chances of staying below 1.5°C following various mitigation scenarios for FFI and LUC CO<sub>2</sub> emissions and non-CO<sub>2</sub> RF**

FFI CO<sub>2</sub> emissions are assumed to decrease linearly to zero in 2035, 2040, 2045, 2050, 2055, or 2060. The colors distinguish the scenarios for non-CO<sub>2</sub> RF, marker shapes differentiate scenarios for CO<sub>2</sub> LUC emissions, while filled and open markers differentiate the time horizon considered for the 1.5°C target (respectively, 2100 and 2300).

in 2100 are similar to or higher than the non-CO<sub>2</sub> RF in the recent past (Figure 1B) requiring stronger CO<sub>2</sub> mitigation to compensate. A possible explanation is that mitigation efforts on non-CO<sub>2</sub> greenhouse gases (GHGs) in those scenarios are not high enough to compensate for the diminution of sulfate aerosols and other short-lived gases, leading to a long-term warming only avoidable with net-negative CO<sub>2</sub> emissions.

Figure 4 displays timeseries, across all model configurations, of the temperature and five relevant Pathfinder variables: atmospheric CO<sub>2</sub> concentration, CO<sub>2</sub> RF, non-CO<sub>2</sub> RF, permafrost emissions, and ocean and land carbon fluxes. It shows that the

model needs a declining total forcing to produce stable temperatures. A declining total forcing is produced by the declining CO<sub>2</sub> RF and the stable non-CO<sub>2</sub> RF after 2100 (Figures 4C and 4D). After 2100, the natural sink of land and ocean is not strong enough to absorb the released CO<sub>2</sub> from permafrost thawing. Therefore, the decline of CO<sub>2</sub> RF after 2100 is too slow and the temperature keeps rising slowly until 2300.

This suggests that even if we stay below 1.5°C by 2100, net-negative emissions in subsequent years will be necessary to stabilize the climate system. However, projections beyond this century are highly model-dependent<sup>3,24</sup> and require further analysis with multiple models. Diagnostics on Pathfinder<sup>10</sup> suggest, for instance, that the ocean carbon storage is slightly overestimated or that the climate-carbon feedback on land is underestimated compared with complex model estimates. These structural differences are accentuated with time and could be a factor influencing the temperature difference between 2100 and 2300.

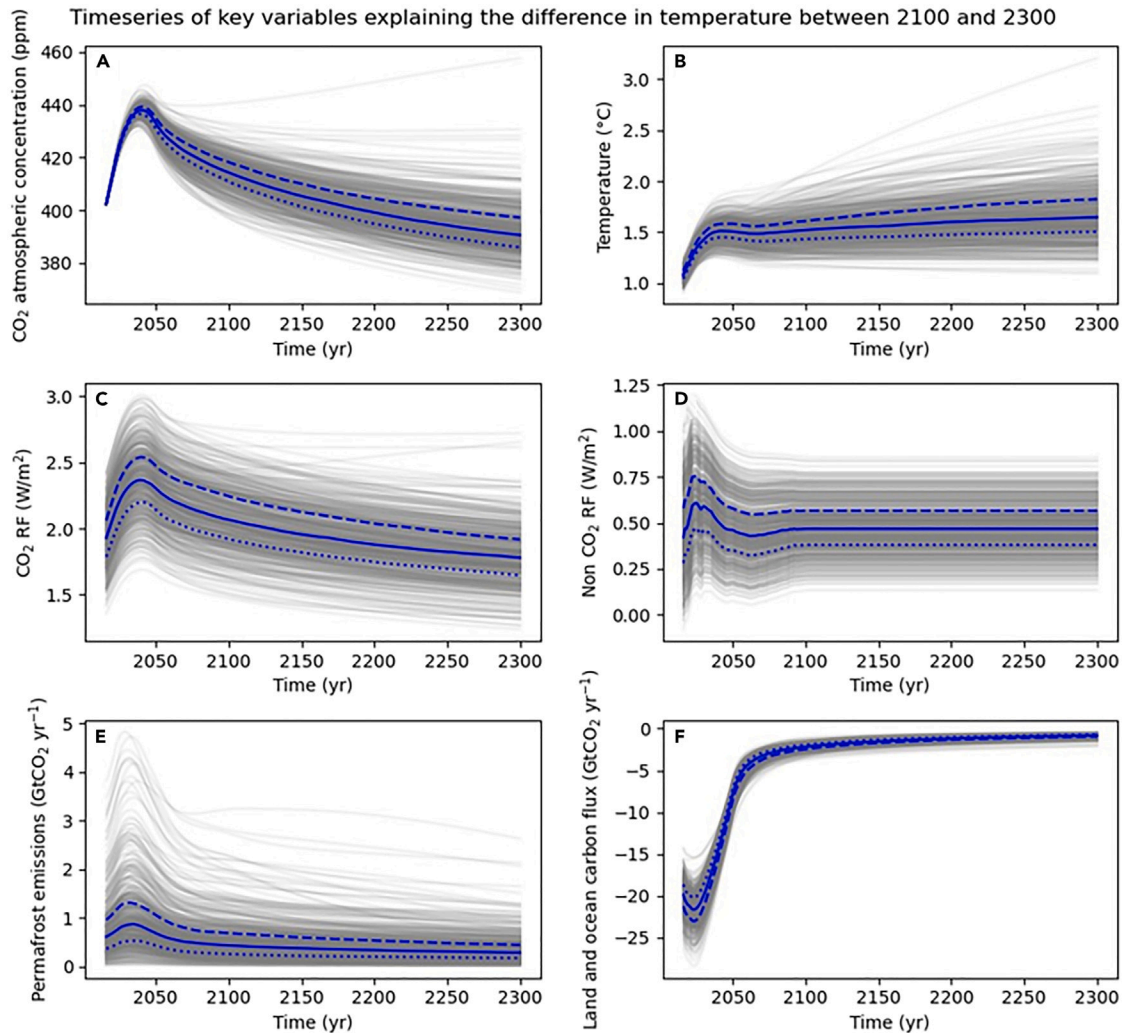
### Chances of staying below 2°C

If net-zero FFI is achieved in 2060 or earlier, chances of staying below 2°C until 2300 were estimated to be 95%–98% with the low non-CO<sub>2</sub> RF scenario. Achieving net-zero FFI emissions in 2050 would provide at least a 55% chance of staying below 2°C under high LUC and high non-CO<sub>2</sub> RF scenarios. Even with net-zero FFI emissions in 2100, there is a 68% chance of staying below 2°C in 2300 under the low non-CO<sub>2</sub> RF scenario, while this drops to a 17% chance under the high non-CO<sub>2</sub> RF scenario (Table 1).

albeit at the cost of being limited by a single model's structure. Despite this conceptual difference, a comparison between the decarbonization rates in our scenarios and the ones implied by the IPCC RCB is informative. Our middle-of-the-road scenario for LUC and non-CO<sub>2</sub> RF combined with a net-zero FFI CO<sub>2</sub> in 2035 results in a 65% chance of staying below 1.5°C. The decarbonization rate (7.7% of 2022 emissions) corresponding to this scenario is similar to the one in the most recent IPCC estimate<sup>11</sup> (after subtracting our central CO<sub>2</sub> LUC emissions) that results in a 50% chance. Therefore, our model appears in the same range as (or slightly more optimistic than) the IPCC estimate.

### Extending the time horizon to 2300

If we extend the time horizon of our analysis to 2300, the chances of staying below 1.5°C systematically drop from 65% to 37% for net-zero FFI in 2035, with medium LUC and non-CO<sub>2</sub> RF scenarios assumed constant after 2100 up to 2300 (Figure 3). The lower chance of staying below 1.5°C over this longer time horizon is due to the long-term dynamics of carbon sinks, which absorb less CO<sub>2</sub> after reaching zero emissions, and of permafrost carbon, which continues to release CO<sub>2</sub> into the atmosphere.<sup>23</sup> Although the overall CO<sub>2</sub> fluxes remains negative because CO<sub>2</sub> concentrations continue to decline after zero emissions are reached (Figure 4A), the speed is insufficient to offset the committed warming caused by non-CO<sub>2</sub> RF. This explains why scenarios with low non-CO<sub>2</sub> RF are least affected by the extension of the time horizon from 2100 to 2300 (Figure 3). Concretely, high and medium non-CO<sub>2</sub> RF scenarios



**Figure 4. Time series showing the evolution of temperature and relevant carbon cycle and climate variables across Pathfinder's configurations**

All trajectories correspond to the medium non-CO<sub>2</sub> RF and medium LUC scenarios with net-zero FFI emissions in 2050. Each gray line corresponds to a different configuration, while the plain blue line gives the median, the dashed blue line gives the 75<sup>th</sup> percentile, and the dotted blue line the 25<sup>th</sup> percentile.

(A) The CO<sub>2</sub> atmospheric concentration.

(B) The temperature.

(C) The CO<sub>2</sub> RF.

(D) The non-CO<sub>2</sub> RF.

(E) Permafrost CO<sub>2</sub> emissions.

(F) The sum of the ocean and land carbon fluxes for all configurations. We observe similar behaviors for any other scenario (not shown).

## DISCUSSION

In this short study, we have examined in detail the uncertainties associated with the chances of staying below the 1.5°C warming limit. With the introduction of this framework, we suggest a move toward an annual assessment using several simple climate models and the most recent emissions published annually.<sup>2,4</sup> Additional models would help verify the reliability of our results and provide a more robust perspective on humanity's actual chances of meeting the 1.5°C target. This assessment could

be done, for instance, simultaneously with the annual carbon budget estimate.<sup>2</sup>

Our idealized scenarios reach net-zero CO<sub>2</sub> FFI emissions assuming no net-negative emissions. In reality, it has been shown<sup>20</sup> that carbon dioxide removal (CDR) will have to be deployed to reach net-zero emissions as some hard-to-abate emissions will remain. Additionally, extending our analysis to the year 2300 underscores the need for models to account for long-term dynamics of carbon sinks and feedback loops such as permafrost. Our results highlight the need to develop

**Table 1. Chances of staying below 2°C following various mitigation scenarios for FFI and LUC CO<sub>2</sub> emissions and non-CO<sub>2</sub> RF**

LUC scenario	Time horizon	Chances of	Chances of	Chances of	Chances of	Chances of	Chances of
		staying below 2°C until 2100	staying below 2°C until 2100	staying below 2°C until 2100	staying below 2°C until 2300	staying below 2°C until 2300	staying below 2°C until 2300
	non-CO <sub>2</sub> RF scenarios	low non- CO <sub>2</sub> RF	medium non-CO <sub>2</sub> RF	high non-CO <sub>2</sub> RF	low non- CO <sub>2</sub> RF	medium non- CO <sub>2</sub> RF	high non-CO <sub>2</sub> RF
Low LUC emissions	net-zero FF in 2050	>99%	>99%	95%	98%	93%	71%
Low LUC emissions	net-zero FF in 2100	95%	81%	51%	80%	51%	28%
Medium LUC emissions	net-zero FF in 2050	>99%	99%	87%	98%	90%	67%
Medium LUC emissions	net-zero FF in 2100	93%	80%	46%	75%	44%	22%
High LUC emissions	net-zero FF in 2050	>99%	99%	86%	97%	83%	55%
High LUC emissions	net-zero FF in 2100	88%	63%	36%	68%	35%	17%

strategies for long-term net-negative emissions,<sup>25</sup> taking into account the diminished capacity of carbon sinks in the distant future.

The importance of non-CO<sub>2</sub> RF on temperature projections is in line with other recent studies using the more widely used RCB methodology.<sup>11</sup> It warrants a closer examination of its individual components, such as methane, nitrous oxide, and pollutants.<sup>14</sup> Although our model focuses primarily on the carbon cycle, a challenge is to develop a method to seamlessly integrate these additional factors into our framework with more detail than the current non-CO<sub>2</sub> RF term that considers all these factors together. Valuable insights could be gained by examining how the different emission pathways of these non-CO<sub>2</sub> factors affect RF and subsequent temperature dynamics. By incorporating these factors, we could refine our understanding of emissions scenarios that are consistent with the 1.5°C target while accounting for the role of non-CO<sub>2</sub> factors.

It should also be noted that the assumption of independent CO<sub>2</sub> and non-CO<sub>2</sub> pathways is a simplification. In particular, SO<sub>2</sub> emissions are strongly linked to CO<sub>2</sub> emissions through common sources. Therefore, a sudden reduction of CO<sub>2</sub> would most probably come with a rise of SO<sub>2</sub> (or aerosols) RF close to the one observed in the high non-CO<sub>2</sub> RF scenario (see Figure 5).

Finally, the 1.5°C target plays a central role in climate negotiations. Today, the mitigation efforts required to meet the 1.5°C target with only a 50% chance are comparable to maintaining FFI CO<sub>2</sub> emissions reduction at a magnitude similar to that caused by COVID-19. This would have to occur every year through 2040, and net emissions would have to be negative thereafter to avoid a rebound effect caused by a decline in the Earth system's capacity to absorb carbon. Although additional efforts to end deforestation and reduce emissions of warming non-CO<sub>2</sub> species such as methane and black carbon would reduce the challenge on the FFI CO<sub>2</sub> side, nothing less than a linear decarbonization rate of 3% year<sup>-1</sup> can preserve these odds. Over the past 5 years, the trend in FFI CO<sub>2</sub> emissions has remained slightly positive at 0.3% year<sup>-1</sup>. Even if emissions

have indeed plateaued, our study shows the huge discrepancy between current efforts and the ones required to meet the ambitious targets that the 1.5°C target sets globally.

## EXPERIMENTAL PROCEDURES

### Resource availability

#### Lead contact

The lead contact is Thomas Bossy: [thomas.bossy@lsce.ipsl.fr](mailto:thomas.bossy@lsce.ipsl.fr).

#### Materials availability

No specific material was used for this study

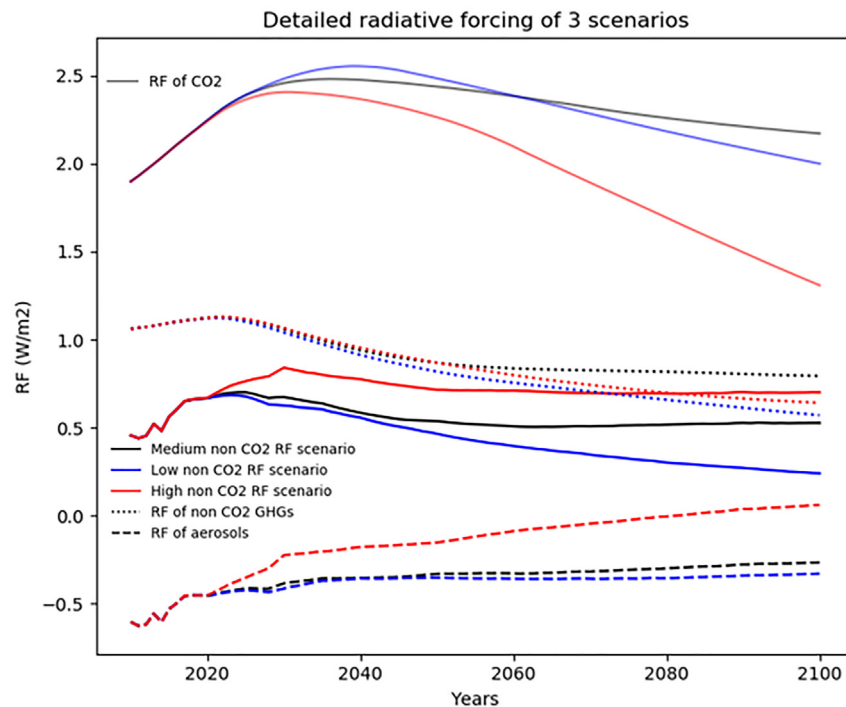
#### Data and code availability

The source code of Pathfinder is openly available at <https://github.com/tgasser/Pathfinder> (last access: 13 March 2023). A frozen version of the code as developed in the paper can be found on Zenodo at <https://doi.org/10.5281/zenodo.7003848>. Additional data available upon request.

We used Pathfinder v1.0.1,<sup>10</sup> a reduced-complexity carbon-climate model. The climate subcomponent that links global mean surface temperature to effective RF follows a widely used 2-box model with deep ocean heat uptake.<sup>26</sup> The ocean carbon cycle follows the structure of the Bern Simple Climate Model.<sup>27</sup> The land carbon cycle was adapted from the compact Earth system model OSCAR.<sup>28</sup> CO<sub>2</sub> emissions from permafrost thaw are globally calculated with the emulator developed by Gasser et al.<sup>23</sup> The 77 model parameters are based on CMIP6 models. 33 parameters are tuned based on existing models and literature, and 44 of them are calibrated through Bayesian inference<sup>29</sup> using observations and assessed values from the latest IPCC report.<sup>10</sup> In particular, we used observations until 2021 to constrain the temperature,<sup>15</sup> the non-CO<sub>2</sub> RF,<sup>17</sup> the CO<sub>2</sub> concentration,<sup>16</sup> and CO<sub>2</sub> emissions,<sup>10</sup> as well as the ocean and land carbon sinks.<sup>10</sup> To account for physical uncertainty, the model is run under 534 different configurations in which the 44 parameters are drawn from the posterior probability distributions obtained after the Bayesian calibration. The configurations were chosen so the historical non-CO<sub>2</sub> RF and the anthropogenic CO<sub>2</sub> emissions remain within the uncertainty range of the most recent estimates. Those estimates were taken in 2022 for CO<sub>2</sub> emissions<sup>10</sup> (36.7 ± 1.8 GtCO<sub>2</sub> year<sup>-1</sup> for FFI and 4.0 ± 2.2 GtCO<sub>2</sub> year<sup>-1</sup> for LUC) and 2019 for non-CO<sub>2</sub> RF<sup>18</sup> (1.16 ± 0.13 W m<sup>-2</sup>). To have the historical starting point of our simulations in 2022, we used the trend of the last 10 years available for non-CO<sub>2</sub> RF to infer the 2020, 2021, and 2022 values (while CO<sub>2</sub> emissions were taken from the latest Global Carbon Budget<sup>2</sup>).

As historical pathways are different in every configuration of the model due to physical uncertainty, the starting point of our future scenarios differs





**Figure 5. Radiative forcing of the three scenarios chosen for low, medium, and high non-CO<sub>2</sub> RF scenarios**

Translucent lines show the CO<sub>2</sub> RF. Solid lines show the total non-CO<sub>2</sub> RF, which can be decomposed in the non-CO<sub>2</sub> GHGs RF contribution (dotted lines), and the RF of all other non-CO<sub>2</sub> forcings (including aerosols such as sulfate) in dashed lines. We observe that a strong reduction of CO<sub>2</sub> RF comes with a rise in aerosols RF, most probably due to the reduction of SO<sub>2</sub> emissions linked to CO<sub>2</sub>. These pathways are the raw scenarios from the AR6 database before rescaling.

depending on the configuration (Figure 1). For FFI CO<sub>2</sub> emissions, we apply a stochastic approach to introduce uncertainty to the historical values consistent with the global carbon budget. The historical values of LUC emissions and their uncertainty are inferred by computing the difference between global anthropogenic total CO<sub>2</sub> emissions obtained from the Pathfinder historical simulations and those from FFI CO<sub>2</sub> emissions. Similarly, we decompose non-CO<sub>2</sub> RF into a component of non-CO<sub>2</sub> greenhouse gases (GHGs) and another component of all other non-CO<sub>2</sub> RF (including aerosols). We apply a similar stochastic approach to non-CO<sub>2</sub> GHGs to incorporate uncertainty, using assessments from the AR6.<sup>13</sup> By subtracting the RF of non-CO<sub>2</sub> GHGs from the overall non-CO<sub>2</sub> RF, we derive the associated uncertainty in the other non-CO<sub>2</sub> RF.

In total we explore 54 scenarios reaching net-zero CO<sub>2</sub> to assess their chances of remaining below 1.5°C. We have 6 possible dates for net-zero FFI CO<sub>2</sub> emissions in 2035, 2040, 2045, 2050, 2055, and 2060. We add net-zero FFI CO<sub>2</sub> emissions in 2100 to estimate chances to remain below 2°C. Those emissions are assumed to decrease linearly to zero at the chosen date and to remain at zero afterwards. To each FFI emission scenario, we associate 3 LUC scenarios and 3 non-CO<sub>2</sub> RF scenarios. The low LUC emission scenario is equivalent to the “end gross forest loss” interpretation of the Glasgow pledge on deforestation.<sup>23</sup> The medium LUC is the “end net forest loss” scenario. High LUC is the “end tree cover loss” scenario. For non-CO<sub>2</sub> RF, we choose 3 scenarios from the C1 category in the latest IPCC report.<sup>19,20</sup> One in the upper range of this set (“MESSAGE-GLOBIOM 1.0-EMF33\_1.5C\_full”), one mid-range (“REMIND-MAGPIE 2.1–4.2-CEMICS\_SSP2-1p5C-minCDR”), and one in the lower range (“REMIND-MAGPIE 2.1–4.2-CEMICS\_SSP1-1p5C-fullCDR”) (see Figure 1). To be consistent with historical values in every configuration of the model, we rescale non-CO<sub>2</sub> RF due to GHGs and other non-CO<sub>2</sub> RF separately.

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#### DECLARATION OF INTERESTS

The authors declare no competing interests.

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