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Research Letter

Lost options commitment: how short-term policies affect long-term scope of action

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Abstract

We propose to explore the sustainability of climate policies based on a novel commitment metric. This metric allows to quantify how future generations' scope of action is affected by short-term climate policy. In an example application, we show that following a moderate emission scenario like SSP2-4.5 will commit future generations to heavily rely on carbon dioxide removal or/and solar radiation modification to avoid unmanageable sea level rise.

Keywords: sustainability; commitment; lost options; generational fairness; vulnerability

Introduction

Climate policy in the coming decades will have profound long-term impacts on global climate, ecosystems and human societies [1, 2]. In this context, *sustainability* is a critical consideration: It pertains to meeting humanities' present needs without compromising the ability of future generations to meet their own. Thus, taking sustainability into account in policy assessments is essential to address climate change while also ensuring intergenerational fairness.

Given the long residence time of CO_2 in the atmosphere and its long-term impacts, taking fair decisions in the upcoming decades requires considering possible scenarios of anthropogenic forcing over timescales of centuries to millennia.

However, in climate policy assessments based on integrated assessment models, longer timescales are often absent, or the long-term impacts of current decisions are heavily discounted relative to short-term impacts [3]. Given that it is challenging to consider longer timescales for multiple reasons, this is understandable, but nevertheless unsatisfactory (or even ethically problematic [4, 5]).

We therefore propose an approach to improving sustainability considerations in climate policy assessments.

Lost options commitment

Our suggestion is to explore the sustainability of short-term climate policies based on a metric, which we call "lost options commitment", that quantifies future generations' scope of action to avoid harmful long-term futures. More particularly, we ask

> "Given a climate state that can be reached under realistic short-time emission scenarios, which long-term climate mitigation options are left to future generations to meet a specified climate target?"

Our method is related to several well-established notions [6] from climate science literature: *climate change commitment* [7], *storylines* [8], *vulnerability* [9, 10] and *mitigation delay sensitivity* [11].

Classical commitment assessments seek to quantify "unavoidable" climate impacts due to inertia in the climate system: a state of the climate system (typically the current one) may be called *committed* to some future impact (like the amount of global warming or sea-level rise) under a given scenario [7, 12–14]. Lost options commitment focuses on the scope of action rather than the impacts: in a given state, humanity is *committed by the lost options* to a narrower scope of action for meeting an intended climate target.

Commitment studies typically rely on few and simplified long-term scenarios, such as *zero emissions*, *constant composition* and *constant emissions* [1, 7, 12–15]. Such simplistic scenarios poorly capture human agency in reacting to climate change, which is one of the key aspects our metric attempts to capture. We adopt Shepherd *et al.*'s storyline approach [8] to compose representative sets of scenarios by combining a small number of building blocks. This modular approach enables the generation of a rich set of long-term scenarios.

For each individual long-term scenario, we may assess the commitment of a climate state with respect to a particular climate variable (e.g. sea-level rise). However, as opposed to traditional commitment studies, we do not stop there. Instead, for a

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given state, we assess the compatibility of each long-term scenario with a chosen *climate target* within a specified *time horizon*. The climate target makes explicit a goal of decision making, e.g. the 1.5°C target of the Paris agreement. The time horizon can be thought of as the "ethical time horizon" of [16].

Scenarios that are compatible with the climate target are considered as *available options* in this state, the others as *lost options*. We may say that in a given state, the *loss of options commits* humanity to a narrower scope of action to meet the desired target. Therefore, we call this metric *lost options commitment* and define the state's *commitment level* as the fraction of the number of options that violate the target to the total number of options considered. Commitment level is reported in units of percentage.

Lost options commitment is a generic metric in the sense that it can be instantiated with different combinations of long-term scenarios, climate targets and timescales. However, it is also itself an instance of the general scheme for vulnerability metrics [9, 10].

We now propose that the sustainability of short-term policies (e.g. given in terms of SSP or RCP emission scenarios) can be analysed by measuring the commitment level of the states encountered when evolving an underlying climate model according to these policies. We argue that by having more climate mitigation options at hand to avoid harmful outcomes (e.g. transgressing specified targets) humanity is in a better position for meeting its needs. Therefore, short-term policies that lead to loss of options, i.e. an increase in the commitment level, should be considered as *unsustainable*. On the other hand, if along the evolution corresponding to a short-term policy the commitment level decreases, this policy increases future generations' scope of action and can be considered as *sustainable*. This approach is well-aligned with the IPCC's 'Window of opportunity to enable climate resilient development' illustrated in Figure 4.2 of the IPCC AR6 Synthesis Report [2] and related to the concept of *robustness* of decisions [17].

The sustainability of short-term policies as suggested above necessarily involves the consideration of multiple targets on multiple timescales. Temperature targets on the year 2100 are normally associated to short-term emission scenarios. The lost options commitment assessment investigates the effect of considering an additional target on a possibly longer timescale. The result of a sustainability assessment relying on lost options commitment, informs us the level of compatibility of a specific short-term scenario (which is compatible with a first target), with the second target. Multiple target considerations have been shown to lead to more stringent policy constraints [18].

Results

We demonstrate our approach with a simple yet instructive example. Our study uses as climate target *avoiding sea level rise above 3 m* within a time horizon of *2000 years* and a set of 45 long-term scenarios as possible options. The horizon is of the same magnitude as the ethical horizon suggested in [16]. The long-term scenarios are generated as combinations of 3 technologies together with usage variants:

- *Dec*—Decarbonisation with rates *slow*, *medium*, *fast*
- *CDR*—Carbon Dioxide Removal with intensities *no*, *weak*, *strong*
- *SRM*—Solar Radiation Modification with possible intensities/durations *no*, *weak short*, *strong short*, *weak long*, *strong long*

Figure A1 provides a visual representation of all the options considered. For the concrete semantics of the scenario building blocks, see Appendix B, where we put in context the different options with respect to the SSP scenarios used in the IPCC WGI AR6 report [19] and motivate their technical feasibility. Given these ingredients, and an appropriate climate model, the lost options commitment can be computed for Earth system states containing a climate state and a current CO_2 emission rate. Here we focus on states that are reached along the SSP scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 from 2020 until 2100, every 10 years, see Fig. A2. Computing the commitment levels requires evolving each of these states along the 45 long-term scenarios for 2000 years, and checking which long-term scenarios comply with the climate target of avoiding sea-level rise above 3 m. For this aim we use the reduced complexity model SURFER [20]. This model has been designed for policy assessments with a long-term perspective, and links CO_2 emissions and solar radiation modification to climate change, ocean acidification and sea level rise. Other greenhouse gasses are absent in the presented example.

Figure 1 shows that following SSP5-8.5 until 2050 leaves the Earth in a state in which more than half of the considered long-term scenarios fail to comply with the chosen climate target. Conversely, following SSP1-2.6 until 2050 results in a state with many available options. Note that sea level simulations up to 2100 do not capture the large differences expected for different states and long-term scenarios, hence the importance (for the chosen target) of looking further in time. States with similar temperature may have different commitment levels, e.g. SSP1-2.6 at 2040 and SSP5-8.5 at 2030 or SSP1-2.6 at 2050 and 2090. One reason for this are the different emission rates associated with these states. This highlights why climate policy negotiations and agreements should look beyond temperature targets.

Figure 2 shows that, as expected, higher emission scenarios lead to fewer available options. The space of options plots for states along SSP2-4.5 and SSP5-8.5 in Fig. 2, show that in 2020, the *slow Dec* options with *no CDR* and with *no SRM* or with *short SRM* do not meet the chosen climate target. By 2030, this is also the case for options with *medium Dec* and *no CDR* with *no SRM* or with *short SRM*. This means that, starting a green transition by 2030, at a rate in line with the SSP scenarios (as the *medium Dec*), will commit future generations to the use of *CDR* or *long SRM* to avoid long-term high sea level rise. By 2050 the use of *CDR* or *long SRM* is inescapable for states reached through SSP2-4.5 and SSP5-8.5 if the climate target is to be respected. Even if most options remain available for SSP2-4.5 at 2050, following this path until 2050 commits future generations to using *CDR* or *long SRM*. Notice that along scenario SSP1-2.6 (top plot in Fig. 2), the commitment level decreases towards the end of the century, with all options becoming available by 2090. This happens because SSP1-2.6 includes CDR from ~2075, see Fig. A2.

Discussion and conclusions

We have exemplified the utility of the *lost options commitment* metric through a specific case, and accompanying sensitivity experiments (detailed in Appendix C) offer insights into its responsiveness to variations in defined parameters. The appendix encompasses a thorough examination of how the metric reacts to changes in critical criteria shaping the problem (e.g. time horizon, target, long-term scenarios) and model parameters like equilibrium climate sensitivity. Furthermore, a dedicated subsection explores the metric's behaviour in the presence of tipping points.

The *lost options commitment* metric currently treats all long-term scenarios with equal weight. Future users, seeking to incorporate cost, feasibility, or risk considerations, may find value in

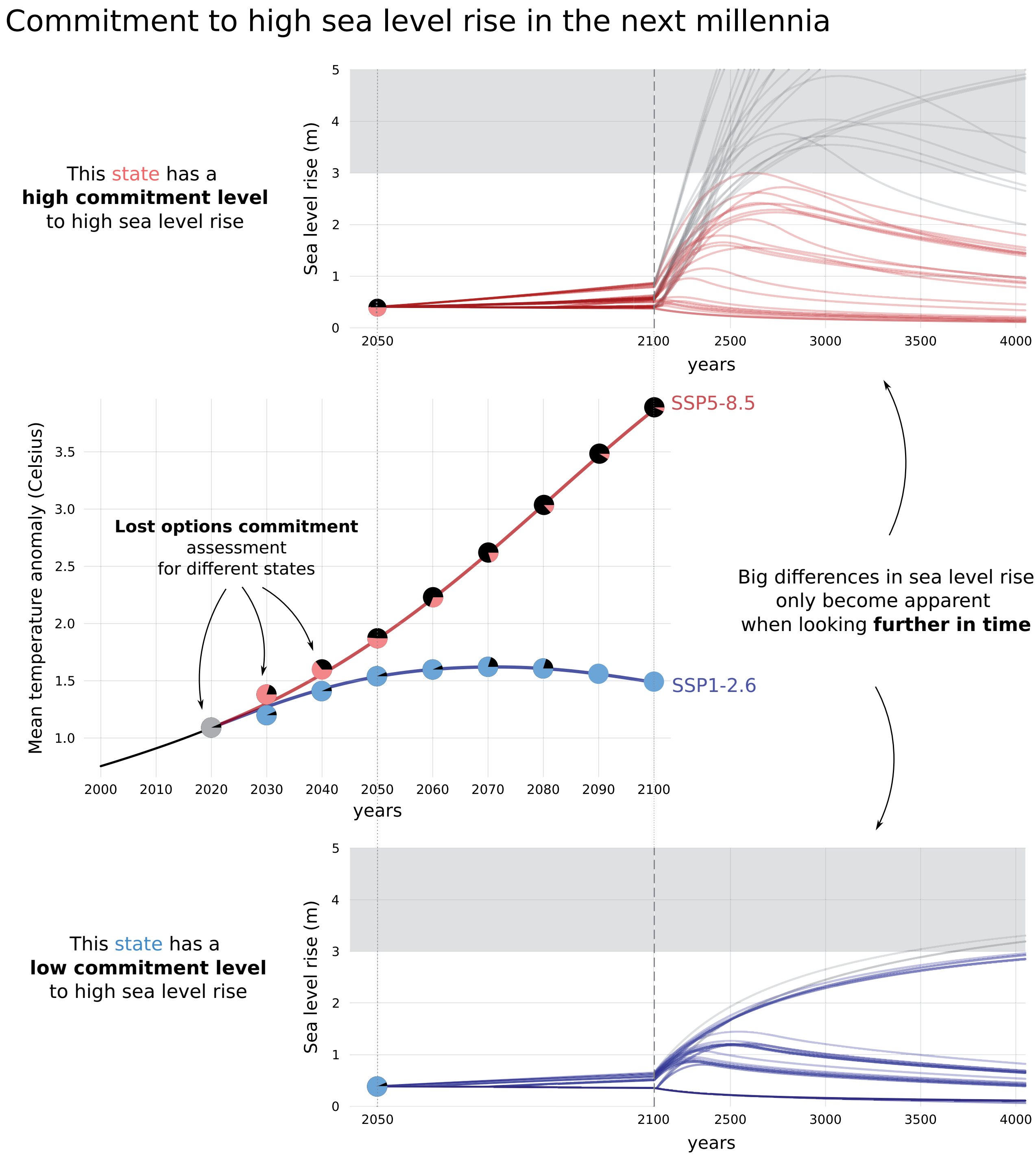

Figure 1. Lost options commitment with respect to high sea level rise in the next millennia. Assessment done for states encountered along SSP5-8.5 and SSP1-2.6. Central plot shows global mean temperature anomaly until 2100 along these scenarios. Pie-chart markers represent the commitment level of the different states: black corresponds to the fraction of long-term scenarios leading to high sea level rise and coloured corresponds to the fraction of long-term scenarios complying with the climate target. Upper and bottom right plots show the sea level rise trajectories for all long-term scenarios considered in the assessment for the states at year 2050 in SSP5-8.5 and SSP1-2.6 respectively. There we show the details of the metric used in this example: sea level rise above 3 meters with respect to pre-industrial anytime in the next 2000 years. Upper and bottom plots contain 45 curves, each of which corresponds to one of the considered possible long-term scenarios. Evolutions leading to high sea level rise are shown in grey and those complying with the climate target have been coloured according to the corresponding SSP scenario the state belongs to.

devising a nuanced metric that assigns distinct weights to each long-term scenario.

In the specific example illustrating the framework's potential application, the constant target implies an equal severity in reaching a 3 m sea level rise by 2200 or 3900. However, the proposed metric's flexibility allows for the consideration of time-varying targets.

Despite the simplicity of the presented example, we think that our study provides valuable insights into the sustainability of the considered SSP scenarios. Thanks to its systematic construction

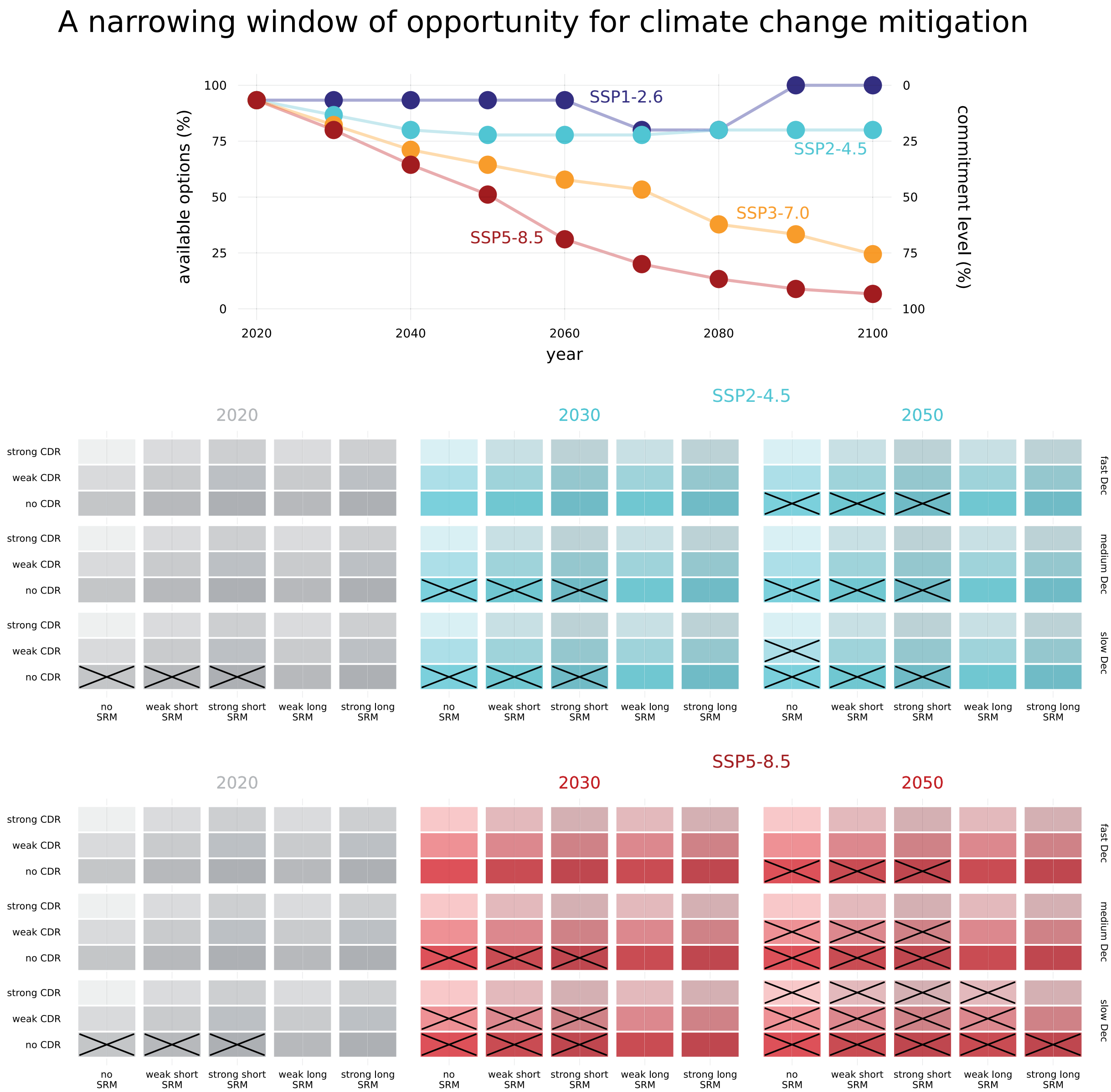

Figure 2. A narrowing window of opportunity for climate change mitigation. Top plot summarises the lost options commitment assessment for states along different SSP scenarios. The bottom plots show, for the states at 2020, 2030 and 2050 along SSP2-4.5 and SSP5-8.5, the outcomes of all the considered long-term scenarios: crossed-out options lead to high sea level rise for that particular state. Similar plots for all the states considered in this assessment can be found in Figs A3–A6.

based on an explicit climate target, time horizon and set of scenarios, the lost option commitment metric is transparent and modular. It also has the advantage of informing policymakers about available options without being prescriptive. In a forthcoming paper we use the commitment level as one of the ingredients of the damage functions of climate policy decision problems, enabling an exploration of trade-offs between long-term and short-term effects. While we do not advocate for prioritizing the first ones over the later, we hope that our metric can contribute to better informed and more sustainable climate decisions.

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Authors’ contributions

Marina Martinez Montero (Conceptualization [lead], Methodology [lead], Software [lead], Visualization [equal], Writing—original draft [lead], Writing—review & editing [equal]), Nuria Brede (Conceptualization [equal], Methodology [equal], Visualization [equal], Writing—review & editing [equal]), Victor Couplet (Conceptualization [equal], Methodology [equal], Visualization-Equal, Writing—review & editing [equal]), Michel Crucifix (Conceptualization [equal], Project administration [lead], Supervision [lead], Visualization [equal], Writing—review &

editing [equal]), Nicola Botta (Visualization [equal], Writing—review & editing [equal]), Claudia Wieners (Visualization [equal], Writing—review & editing [equal]).

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Conflict of interest

No competing interest is declared.

Data Availability

The code underlying this article is available in Zenodo, at https://zenodo.org/doi/10.5281/zenodo.10688672.

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Appendices

A. Extended Data

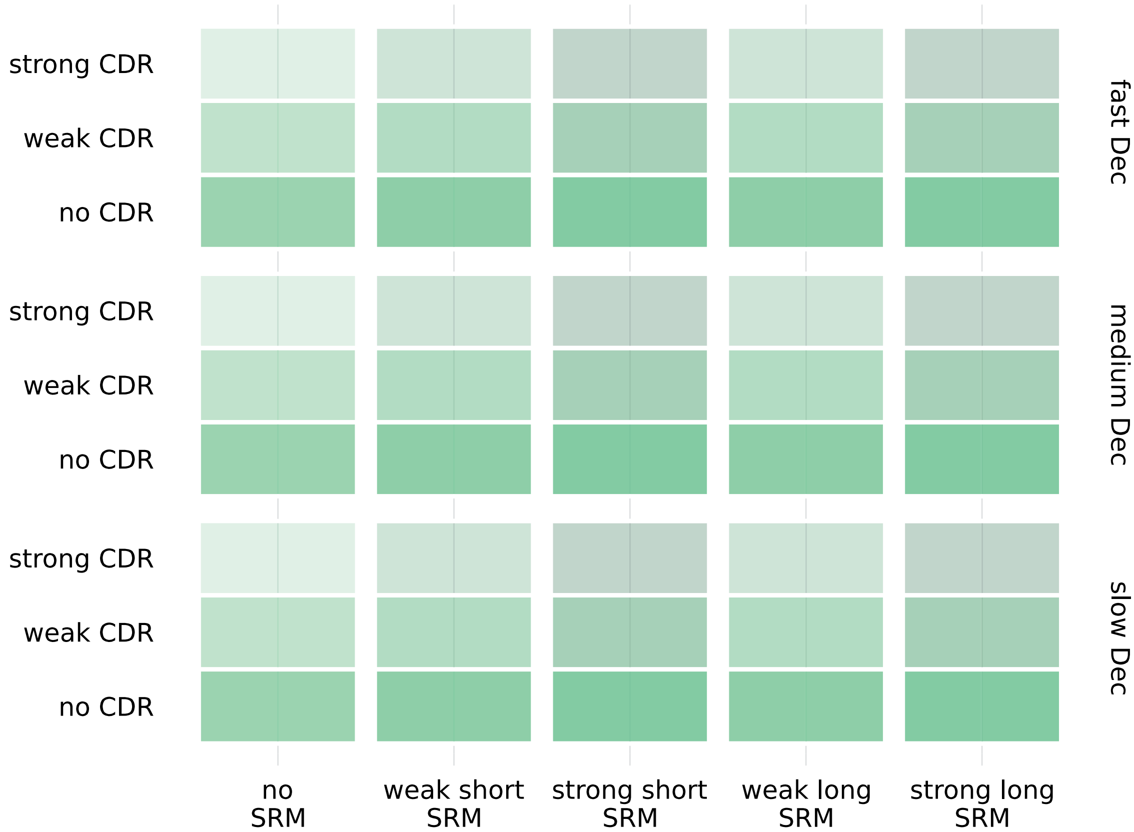

Figure A1. The 45 long-term scenarios considered in the lost options commitment assessment decomposed into different groups. Each column corresponds to a different solar radiation modification option. Rows are divided into groups of three, each of these groups corresponds to different decarbonisation options (right labels). Within each decarbonisation group, the three rows represent different carbon dioxide removal options (left labels).

B. Methods

To perform the lost options commitment assessment we have relied on the SURFER model [20]. This model has two forcing sources, one corresponding to CO_2 emissions (E), and another one corresponding to SRM SO_2 injections (I). The different long-term scenarios present in the lost options commitment assessment correspond to different definitions of these emissions and injections over the assessment period.

The 45 long-term scenarios are constructed as a Cartesian product of three sets of options corresponding to different decarbonisation rates, solar radiation modification intensities and durations, and carbon dioxide removal rates.

Three constant decarbonisation rates are considered: –0.08, –0.25 and –0.75 PgC/year^2. The medium decarbonisation rate (–0.25 PgC/year^2) approximately aligns with the decarbonisation rates present in SSP1-2.6 and SSP4-3.4 while the fast one (–0.75 PgC/year^2) is a limit case that aligns with the decarbonisation rate present in the overshoot scenario SSP5-3.4-OS. We model the decarbonisation options by reducing emissions linearly decrease at the specified rate until zero emissions are reached. When applied to a state with zero or negative emissions the three decarbonisation options are degenerate and have no effect.

Five solar radiation modification options are considered: *none*, *weak short*, *strong short*, *weak long*, *strong long*. SRM is used to counter-act all possible global warming and it is achieved through stratospheric aerosol injections. The weak and strong intensities correspond to maximum injection rates of 20 and 40 MtS/yr. The weak intensity corresponds roughly to the injection rates required to reduce the radiative forcing of a high emission scenario like SSP5-8.5 to that of SSP2-4.5 by year 2100 [21, 22], the strong intensity is twice the weak rate. These rates, while high, fall within the SRM scenarios covered by the SRM literature referenced in the IPCC WGIII AR6 report, see Cross-Working Group Box 4—Solar Radiation Modification in [23]. SRM options are applied “smartly” such that just the necessary amount of aerosols is injected to return to pre-industrial temperatures. In SURFER, the precise injection rate needed to flow towards a δT_{target} is

$$I_{\text{needed}} = \beta_{SO_2} \times \left(-\log\left(\frac{F_{CO_2}(M_A) - \beta\delta T_{\text{target}} + \gamma(\delta T_D - \delta T_{\text{target}})}{\alpha_{SO_2}}\right)\right)^{-1/\gamma_{SO_2}} \quad (1)$$

where M_A is the carbon mass in the atmosphere, F_{CO_2} is the CO_2 radiative forcing and δT_D is the temperature anomaly of the deeper ocean layer. This equation was obtained by solving

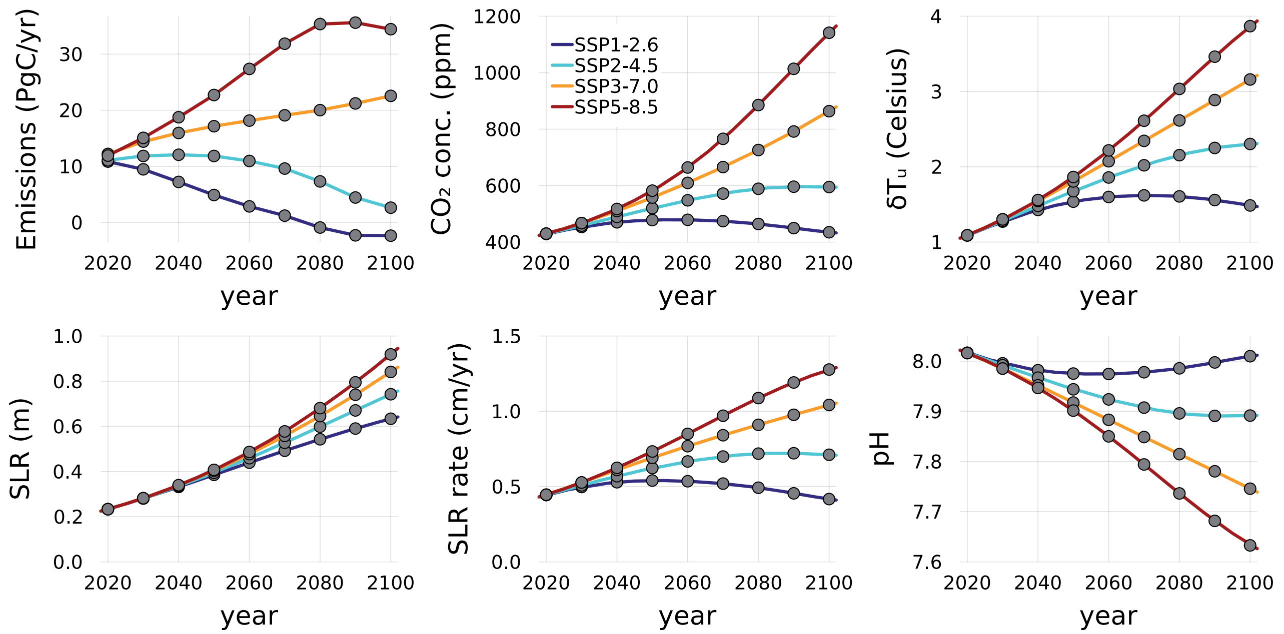

Figure A2. States on which lost options commitment assessment is performed, in grey. Each plot refers to a different quantity characterising the state. From left to right, top to bottom: emission rate, atmospheric CO_2 concentration, mean temperature anomaly, sea level rise, sea level rise rate, upper ocean pH.

$$\frac{d\delta T_U}{dt} = 0 \tag{2}$$

for $I = I_{\text{needed}}$ with $\delta T_U = \delta T_{\text{target}}$ in Equation (29) of [20], where δT_U is the temperature anomaly of the upper ocean layer which is taken as the global mean temperature anomaly. We set $\delta T_{\text{target}} = 0°\text{C}$. The injection rate used is then

$$I_{\text{used}} = \min\{\text{SRM}_{\text{limit}}, I_{\text{needed}}\} \tag{3}$$

where $\text{SRM}_{\text{limit}}$ is 20 or 40 MtS/yr depending on the long-term scenario. We consider two durations for injection deployment, *short* and *long*. We define *short* as the time it takes to achieve full decarbonisation and *long* to the whole commitment assessment timescale. In the sensitivity analysis presented in Sec. C we consider other definitions of *short* which are longer than the decarbonisation period.

Three constant atmospheric carbon dioxide removal rates are considered: 0, −1, −2 PgC/year. The strong carbon dioxide removal rate approximately coincides with the one in the SSP1-2.6. There are other SSP scenarios with higher CDR rates, up to more than twice as large for the overshoot scenario SSP5-3.4-OS. We model CDR options by starting since the beginning of the assessment. If decarbonisation has not finished for the particular state there is an immediate reduction in net emissions. CDR continues at the specified constant rate after decarbonisation has ended and until pre-industrial atmospheric CO_2 concentration is reached. The CDR rate is then reduced so that it just removes the carbon that flows into the atmosphere from land and ocean, keeping atmospheric concentrations constant at pre-industrial levels until all reservoirs return to pre-industrial conditions. The reduced removal rate is obtained by setting $M_A = M_A(t_{PI})$ in Eq. (27a) of [20] and solving for the emissions in

$$\frac{dM_A}{dt} = 0, \tag{4}$$

which gives

$$E_{\text{CDR reduced}} = k_{A\to U}\left(M_A(t_{PI}) - \frac{m_A}{W_U K_0} B(M_U) M_U\right) - k_{A\to L}\left(M_L - M_L(t_{PI})\right). \tag{5}$$

For details on all the terms in equations (1) and (5), parameter values and pre-industrial conditions we refer the reader to [20].

We consider all the defined decarbonisation and carbon dioxide removal options to be technically feasible, since our strongest Dec and CDR rates align with those of strongly mitigating SSP scenarios, which are themselves deemed technically feasible [23, page 435]. The *short* SRM options seem to be both technically [24] and physically [22] feasible even if the rates considered are high.

For any given state, the assessment is done by considering 45 different evolutions. Each evolution obtained by evolving the particular state forced by a different long-term scenario, which specifies the emission and injection forcings, for 2000 years. This results in 45 trajectories, each corresponding to a different long-term scenario. Each trajectory is then inspected against the chosen target, in the presented example, whether sea level rise is higher than 3 meters above pre-industrial values within those 2000 years. We integrate SURFER's differential equations in Julia using the package `DifferentialEquations.jl` with the integration method `Rosenbrock23()`, `abstol = 1e-12` and `reltol = 1e-3`.

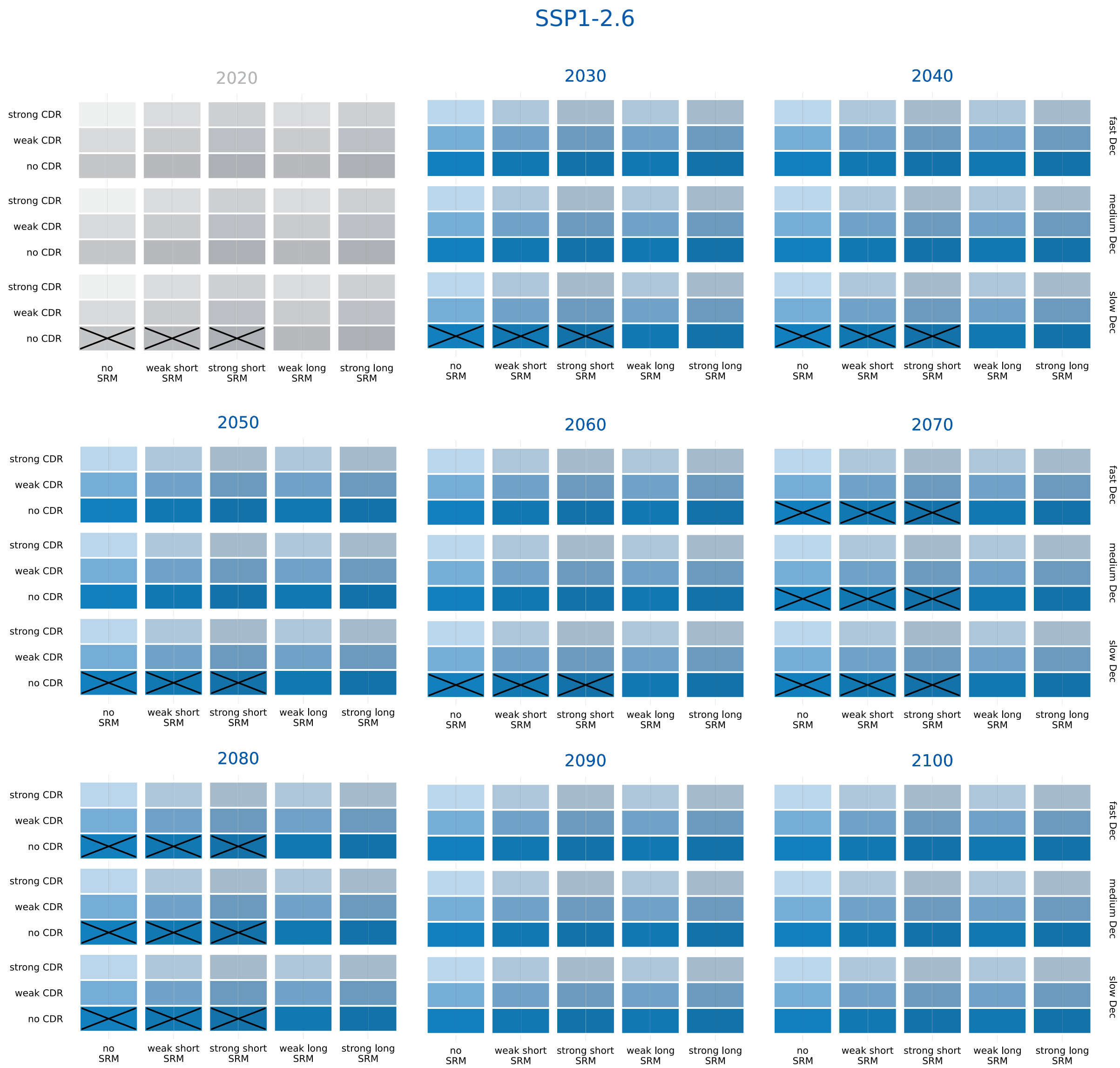

Figure A3. A window of opportunity along SSP1-2.6. The space of considered long-term scenarios is shown for the states assessed. Options that transgress the target are crossed out.

C. Sensitivity experiments

The lost options commitment assessment needs the specification of three ingredients:

- time horizon
- target
- long-term scenarios (space of options)

The results of the assessment will then, by construction, depend on these ingredients, which define the nature of the assessment itself. Model parameters, e.g. equilibrium climate sensitivity, tipping point thresholds and ocean circulation timescale, will also impact the results. However, for the assessment to be useful and reasonable, robustness to small changes in criteria or parameters is required. In what follows, we perform four sensitivity analyses for the example discussed in the main text and discuss how the presence of tipping points in the climate system might impact our metric.

C.1 Sensitivity to time horizon

First we explore the sensitivity of the commitment level to the time horizon. We repeat the main text example for 30 equally spaced time horizons from 500 to 4000 years, see Fig. C1. There we see several things:

1. Longer horizons result in higher commitment levels. This is because sea level rise is a slow process. If the horizon is too short, a given option might respect the specified target, while when extending the horizon that same option might lead to target transgression.
2. However, for horizons of 2500 to 4000 years, the metric converges because:
   a) Only some of the long-term scenarios exhibit temperatures that correspond to committed sea level rise higher than the target. Long-term scenarios that do not exhibit high temperatures for long enough do not lead to high sea level rise, no matter how long the time horizon.

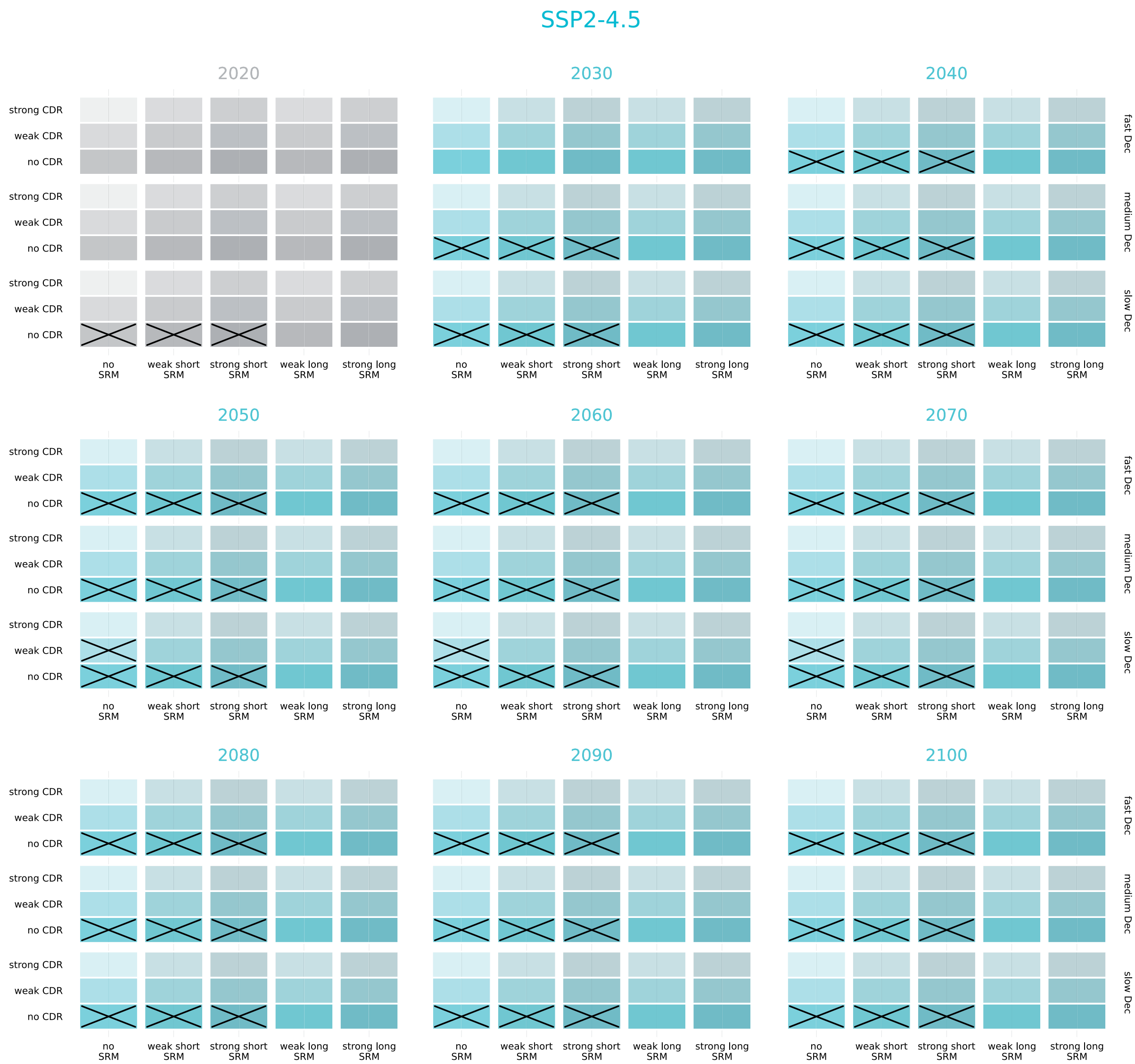

Figure A4. A narrowing window of opportunity along SSP2-4.5. The space of considered long-term scenarios is shown for the states assessed. Options that transgress the target are crossed out.

b) A large fraction of the committed sea level rise happens within the next 3000 years, after that time, all options that would eventually transgress the target of 3m have already done so.

3. The presence of ice sheet tipping points in SURFER is not apparent in these particular results. This is reasonable since the target of 3m is lower than the sea level rise potential of Greenland ice sheet, which is around 7m, and hence does not differentiate between tipping and non-tipping options.

C.2 Sensitivity to targets

Second, we analyse the sensitivity to the target, specifically, to the threshold chosen for sea level rise. We repeat the example in the main text, but with varying thresholds from 1 to 5 meters, see Fig. C2. There we see that:

1. Lower SLR thresholds lead to higher commitment levels.
2. Gradual changes in SLR threshold lead to gradual changes in commitment levels. States along SSP1-2.6 after 2070 are an exception to this.
3. For states after 2070 along of SSP1-2.6 certain ranges of targets exhibit degenerate commitment levels. In particular, by 2100, all considered thresholds (400) collapse into 4 groups with commitment levels: 0%, 20%, 40% and 60%. This can be understood due the big degeneracy in the long-term scenarios due to the fact that decarbonisation has finished:
   a) The three decarbonisation speeds are degenerate in this case.
   b) The *short SRM* options (defined to happen during decarbonisation) are degenerate with the *no SRM* option.

The available options corresponding to these four groups can be found in Fig. C3. Focusing on the 60% commitment level group, which corresponds to relatively low sea level rise thresholds, we see that CDR rates considered in the long-term scenarios are not large enough to stop a sea level rise of 1 meter in the next 2000 years without relying on SRM for the state corresponding to SSP1-2.6 at 2100.

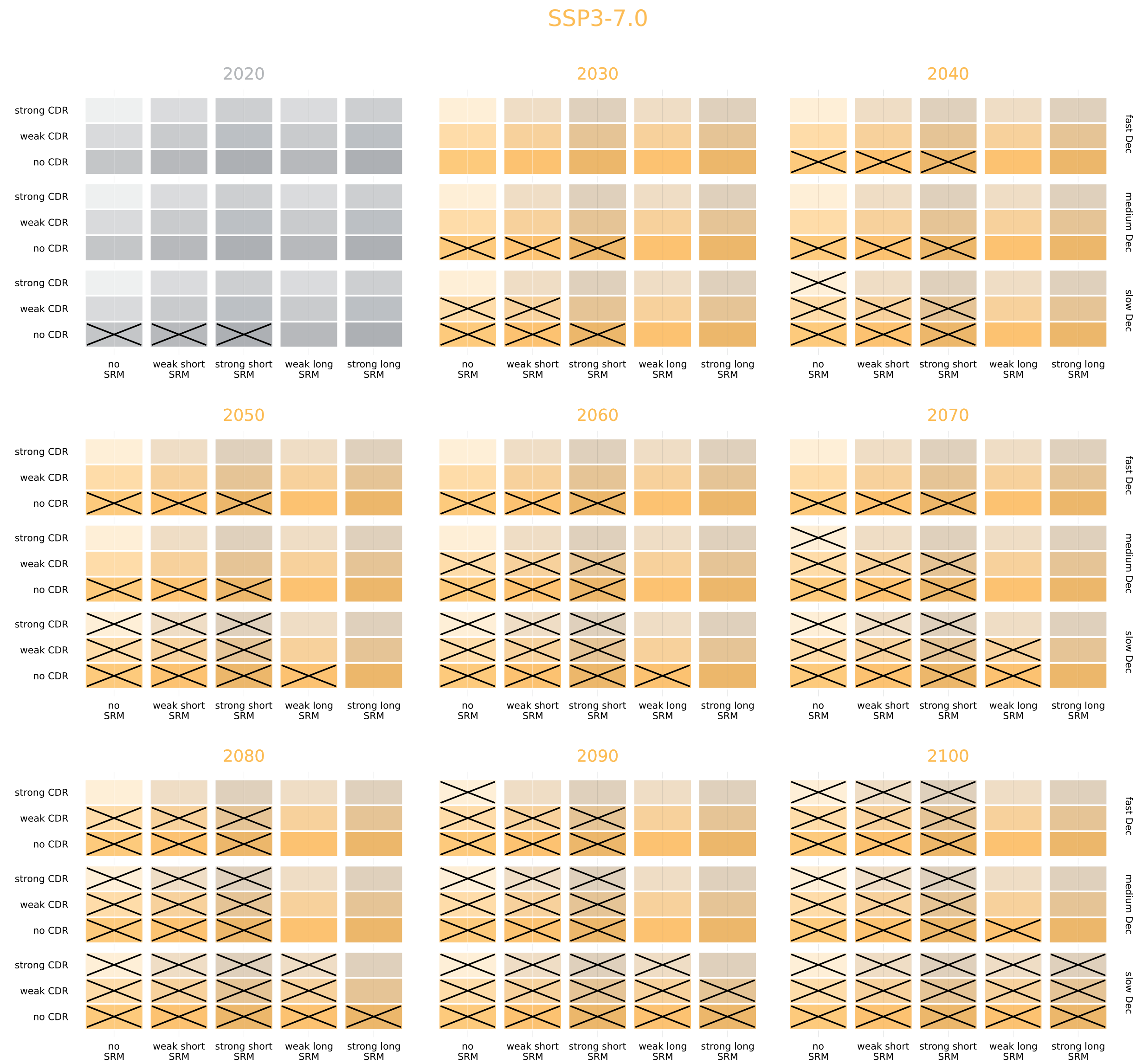

Figure A5. A narrowing window of opportunity along SSP3-7.0. The space of considered long-term scenarios is shown for the states assessed. Options that transgress the target are crossed out.

C.3 Sensitivity to long-term scenarios

In Figs. A3–A6 we see an almost absolute degeneracy between the long-term scenarios that have *no SRM* and those that have *short SRM*. This suggests that SRM until the end of decarbonisation is too short to have a significant impact—especially in the absence of CDR, as was already shown by [25]. In such scenarios, SRM stops shortly after the peak in CO_2 concentration. For this reason, we consider different definitions of *short SRM*, and assess the sensitivity of the lost options commitment assessment to these definitions. Specifically, we set the duration of *short SRM* to be that of decarbonisation plus an extension which ranges from 0 to 300 years. This corresponds to a policy of buying enough time for natural feedbacks to kick in. Fig. C4 shows that overall, extending the duration of *short* SRM deployement decreases the commitment level, as expected. The effect is relatively small for medium and high emission scenarios (SSP2-4.5, SSP3-7.0 and SSP5-8.5) but is more significant for SSP1-2.6, in 2070 and 2080. Figures C5–C8 show the space of options for different *short SRM* durations for a particular state. Extending the duration of *short SRM* has the effect of buying time and making some of the transgressing options viable ones. Depending on the emission rate associated to the state being assessed, the liberated options are different:

- For SSP1-2.6 in year 2070 decarbonisation has almost finished, see Fig. A2. Extending the *short SRM* period frees up the options with *no CDR*, *short SRM* independently of the decarbonisation rate, see Fig. C5, i.e. it buys time for natural sinks to kick in.
- For SSP2-4.5 in year 2040 emissions are high, see Fig. A2. Extending the *short SRM* period frees up the options with *fast Dec*, *no CDR*, *short SRM*, see Fig. C6. In this case SRM also buys time for natural sinks to kick in. Notice however that it does not buy enough time for *medium Dec* and *slow Dec* to become viable.
- For SSP3-7.0 in year 2050, we see in Fig. C7 that extending the *short SRM* period enables the options with *slow Dec*, *strong CDR*, *short SRM*. In this case a longer *short SRM* period

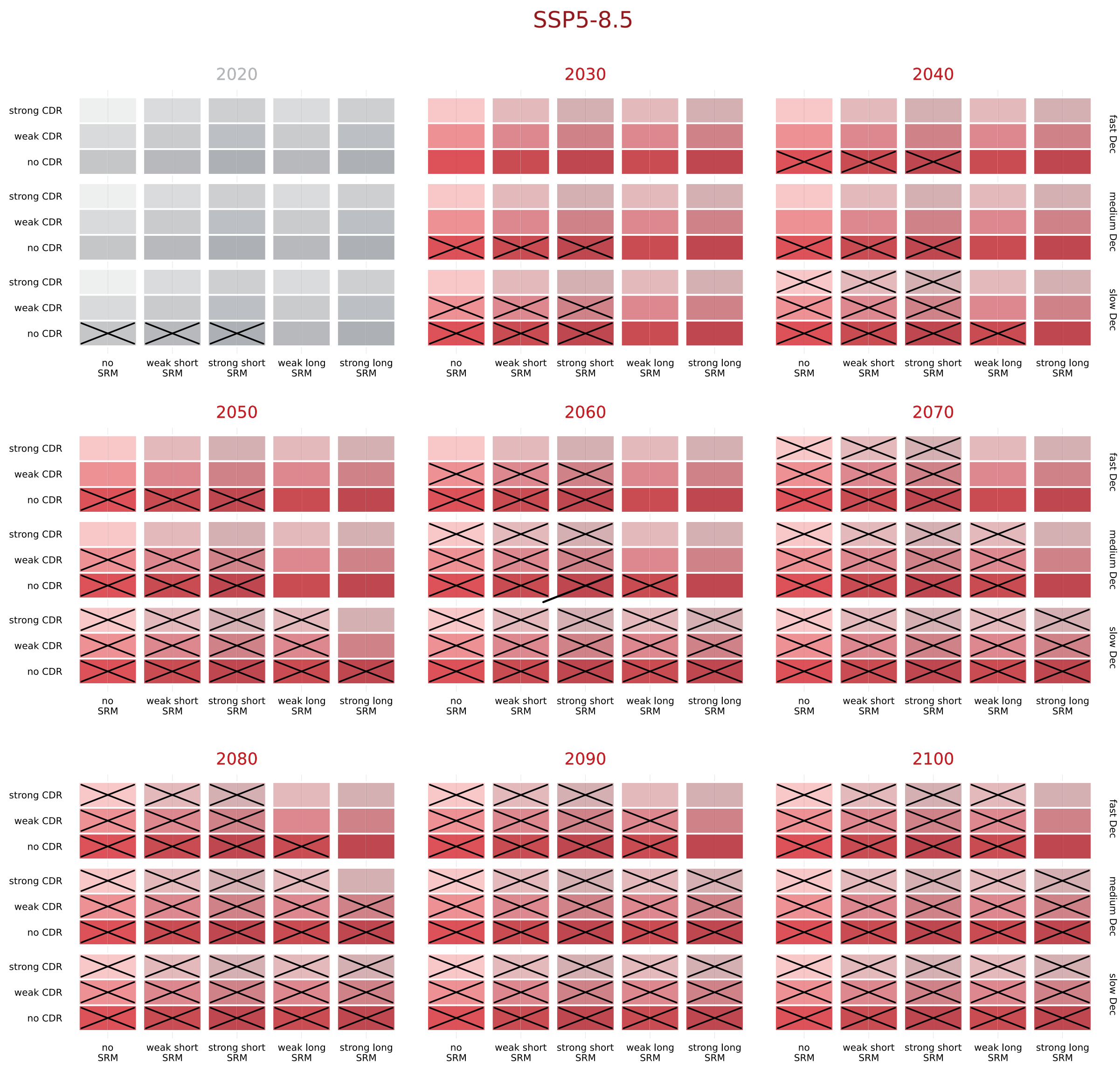

Figure A6. A narrowing window of opportunity along SSP5-8.5. The space of considered long-term scenarios is shown for the states assessed. Options that transgress the target are crossed out.

allows for a slower decabonisation with strong CDR deployment to be a viable option.

- Finally, for SSP5-8.5 in year 2060, Fig. C8, extending the *short SRM* period enables the options with *fast Dec, medium CDR, short SRM* and extending it further, the options with *medium Dec, strong CDR, short SRM*.

C.4 Sensitivity to model parameters

Now we focus on the sensitivity of commitment level to model parameters. Climate models, even reduced complexity ones as SURFER contain many parameters. Here we perform a sensitivity analysis only for the equilibrium climate sensitivity. This is the amount of expected warming at equilibrium, for a doubling of CO2 concentration, and it is one of the most discussed about quantities in the science—policy intersection. In SURFER it is explicitly set as a parameter, but in most earth system climate models, it is computed based on the results of some experiments. Its value is uncertain, the IPCC WGI AR6 [19] reports a *very likely* range between 2.0°C and 5.0°C, a *likely* range between 2.5°C and 4.0°C and a best estimate of 3°C. The sensitivity experiment shown in Fig. C9, considered seven different values of equilibrium climate sensitivity: 2.0°C, 2.5°C, 3.0°C, 3.5°C, 4.0°C, 4.5°C and 5.0°C, this range coincides with the aforementioned *very likely* range. There we see that expected, higher values of climate sensitivity lead to higher commitment levels. This is reasonable since the same CO_2 concentrations would lead to higher temperatures and hence higher sea level rise. We also notice that the variation induced by the unknown value of equilibrium climate sensitivity is of the same order as the one induced by changes in the definitions of the commitment metric: time horizon and threshold, at least for the ranges of time horizon and thresolds explored.

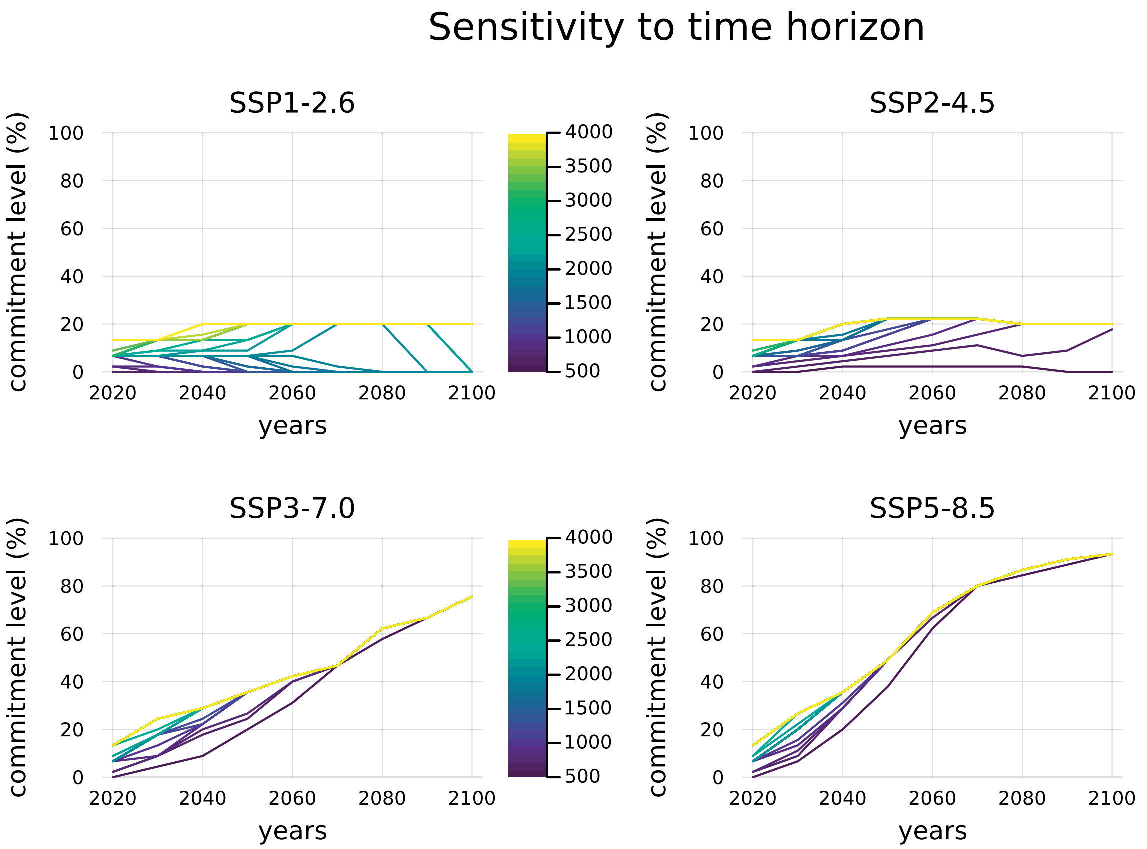

Figure C1. Sensitivity of commitment level to time horizon. Commitment level for states along the different SSP scenarios (as top panel of Fig. 2, y-axis inverted). Each panel corresponds to a different SSP scenario. Each line, within each panel, corresponds to the commitment assessment for a different time horizon where the line color encodes the horizon used (see side color bar). 30 equally spaced time horizons have been considered in the range between 500 to 4000 years. The target is always fixed as sea level rise lower than 3 meters within the corresponding time horizon. The units of the color bar are years.

C.5 Ice sheet tipping points and lost options commitment

We have stated that for the metric to be useful and reasonable some robustness to small criteria variations is required. We see two caveats to this argument. First, lost options commitment could be sensitive to very small variations in the target if several of the long-term scenarios produce similar or identical trajectories. This is what we observed for states after 2070 along of SSP1-2.6 in Fig. C2. Second, lost options commitment could be sensitive to very small variations in the time horizon if abrupt changes are observed in the target variable. This could typically happen in the presence of fast climate tipping elements. In this particular study, however, the only tipping elements considered are the ice sheets, which exhibit slow dynamics, and so we don't expect our metric to be very sensitive to small changes in the time horizon.

In the presented sensitivity analyses of the previous sections, the ice sheet tipping points present in the SURFER model did not have an effect on the lost options commitment assessment. These analyses, however, were by design incapable of showcasing such an effect because of two reasons:

1. We did not explore a big enough sea level rise target.
2. We did not explore big enough time horizons.

Ice sheets are modelled in SURFER via a non-linear ordinary differential equation, see Equation (38) in [20]. That particular equation, which has been fitted to Greenland and Antarctica separately, encodes tipping points and bi-stability behaviour for both of the ice sheets and has been shown to agree with the steady states and dynamics of three dimensional ice sheet models [20]. Fig. C10 shows the sea level rise bifurcation diagram of the SURFER model in its default setup, which includes contributions from glaciers and ocean thermal expansion as well as the ice sheets. There we see two tipping points as temperature is increased from pre-industrial conditions. The first bifurcation point encountered, as temperature is increased (around 1.52°C), corresponds to Greenland's tipping point and the second one (around 6.8°C) corresponds to Antarctica's tipping point.

In the default setup of the SURFER model [20], Greenland's ice sheet tipping point is at a global mean temperature anomaly of 1.52°C. The committed sea level rise from all sea level rise contributors at that temperature corresponds to ≈ 5.9m for the state with ice on Greenland and to more than 10 m for the state with ice free Greenland, see Fig. C10. In order to see whether Greenland's ice sheet tipping point has an effect on the commitment assessment, the sea level rise target should be set to 5.9 m or larger. We repeated the target sensitivity experiment for sea level rise targets from 1 m to 10 m for states along SSP2-4.5 considering a time horizon of 5kyr and a time horizon of 50kyr, see Fig. C11. For both considered horizons we see that gradual changes in the target lead to gradual differences in the commitment level. There we see increases in the commitment level of consecutive states for different climate targets. For targets smaller than ∼ 5.9m those increases are not necessarily related

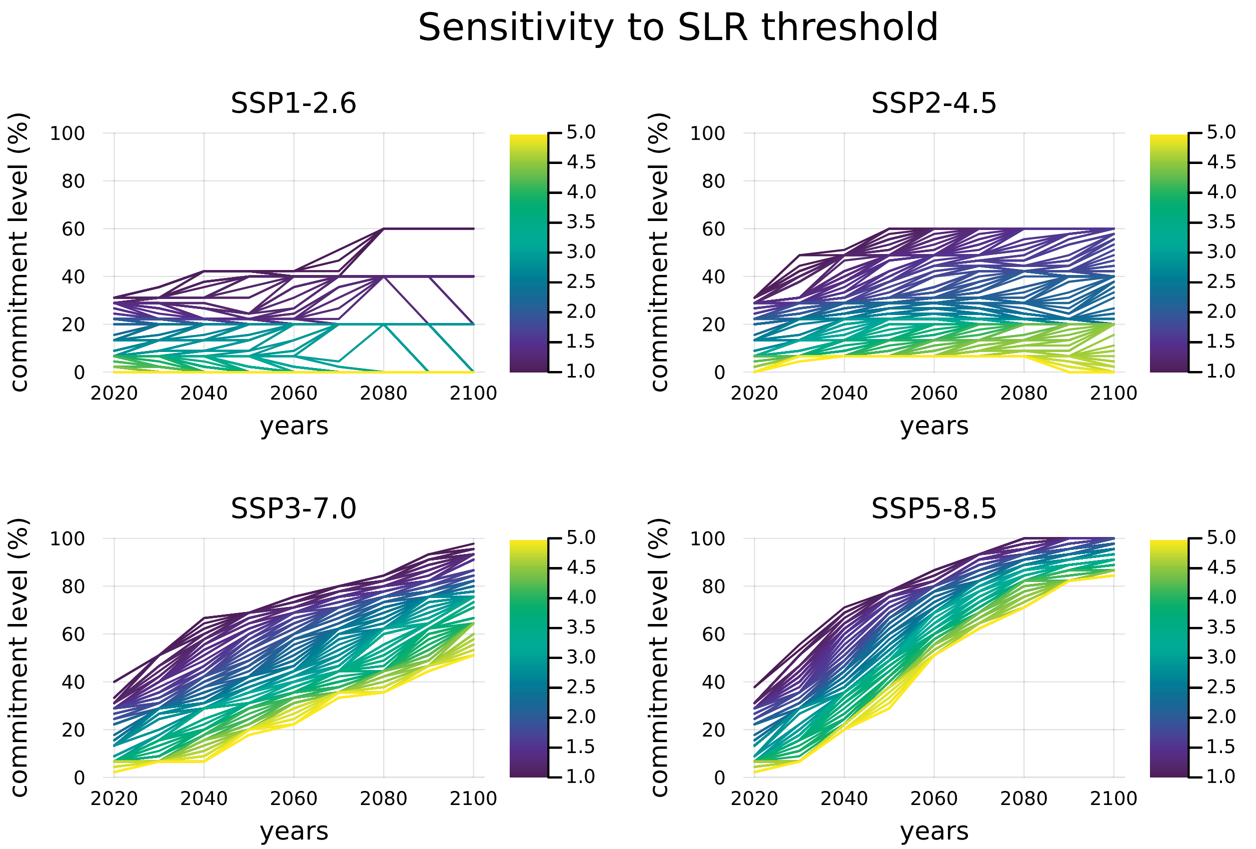

Figure C2. Sensitivity of commitment level to sea level rise target. Commitment level for states along the different SSP scenarios (as top panel of Fig. 2, y-axis inverted). Each panel corresponds to a different SSP scenario. Each line, within each panel, corresponds to the commitment assessment for a different sea level rise target where the line color encodes the target used (see side color bar). 400 targets have been considered in the range between 1 to 5 meters. The time horizon has been fixed at 2000 years. The units of the color bar are meters.

Figure C3. Available options corresponding to degenerate commitment levels along SSP1-2.6 in 2100, for the threshold sensitivity experiment, see year 2100 in top left panel of Fig. C2. The percentage in the panel title indicates the commitment level of the given degenerate group. The 0% panel corresponds to higher thresholds while the 60% panel corresponds to lower thresholds.

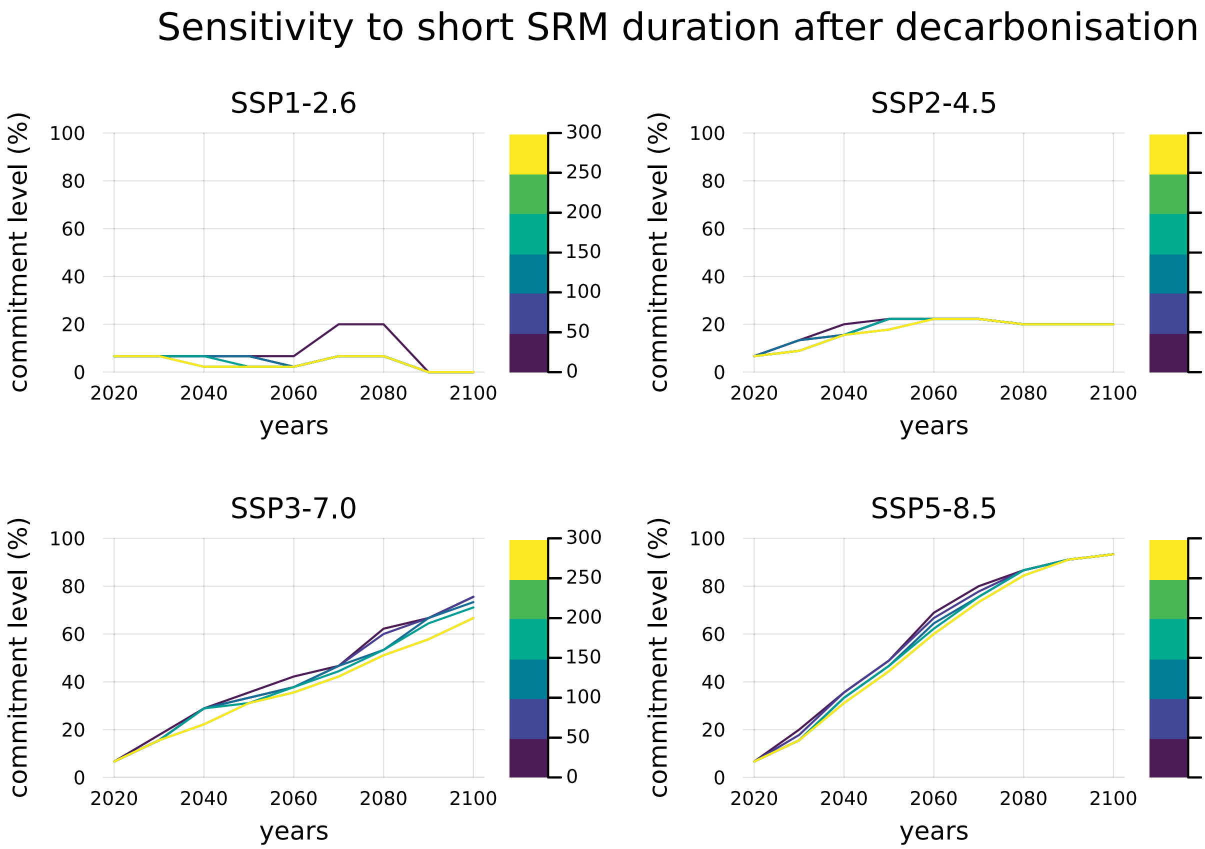

Figure C4. Sensitivity of commitment level to the duration of the *short SRM* options. Commitment level for states along the different SSP scenarios (as top panel of Fig. 2, y-axis inverted). Each panel corresponds to a different SSP scenario. Each line, within each panel, corresponds to the commitment assessment for a different duration of the *short SRM* options. The color scale corresponds to the years of continued SRM, on the *short SRM* options, after decarbonisation has finished. The time horizon has been fixed at 2000 years and the threshold to 3 m of sea level rise within those 2000 years.

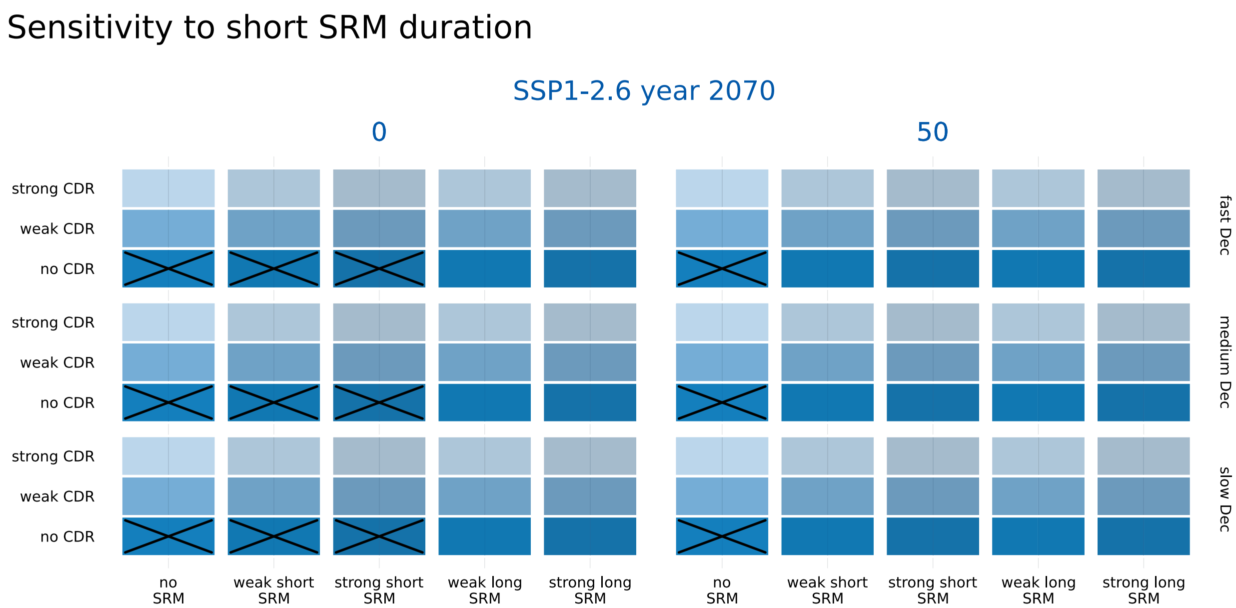

Figure C5. Sensitivity of available options to *short SRM* duration for SSP1-2.6 in year 2070. The numbers indicate the years of continued SRM after decarbonisation has finished. Only the columns corresponding to *short SRM* are subject to change.

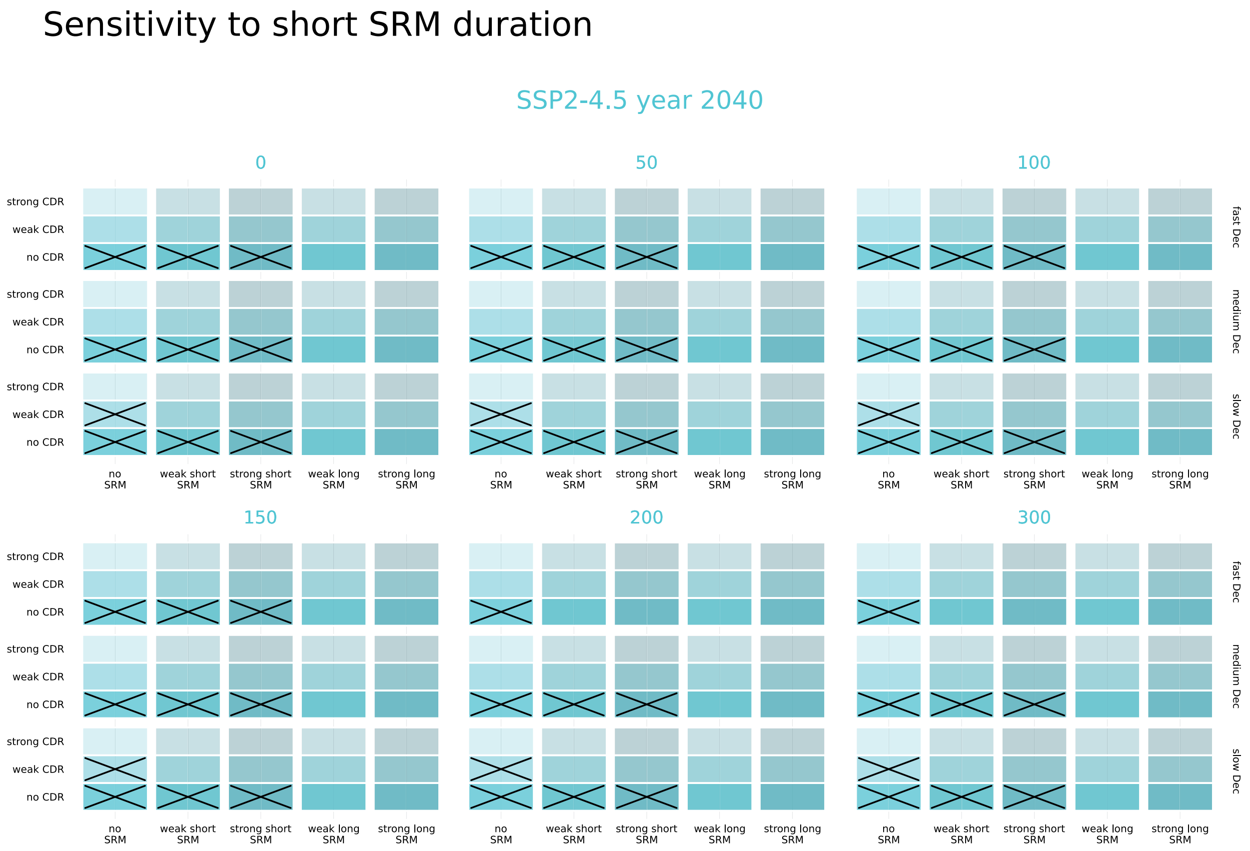

Figure C6. Sensitivity of available options to *short SRM* duration for SSP2-4.5 in year 2040. The numbers indicate the years of continued SRM after decarbonisation has finished. Only the columns corresponding to *short SRM* are subject to change.

Sensitivity to short SRM duration

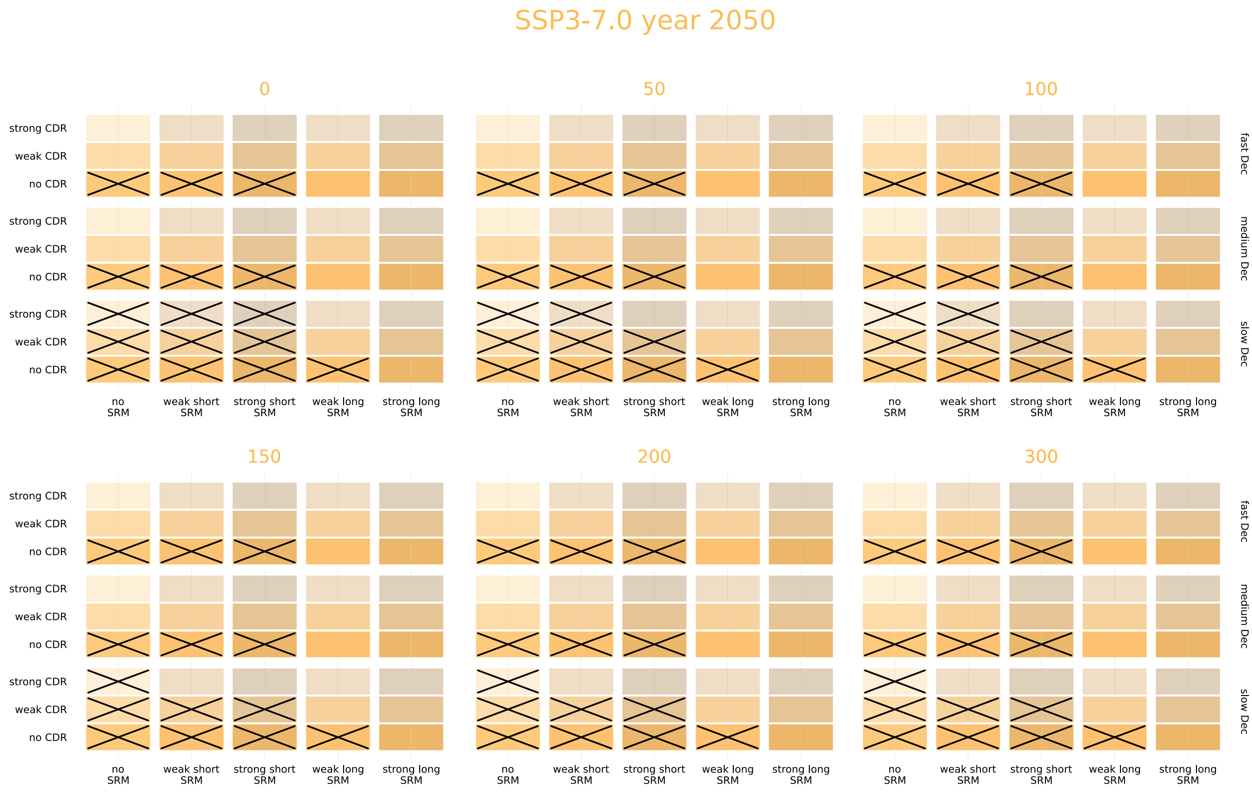

Figure C7. Sensitivity of available options to *short SRM* duration for SSP3-7.0 in year 2050. The numbers indicate the years of continued SRM after decarbonisation has finished. Only the columns corresponding to *short SRM* are subject to change.

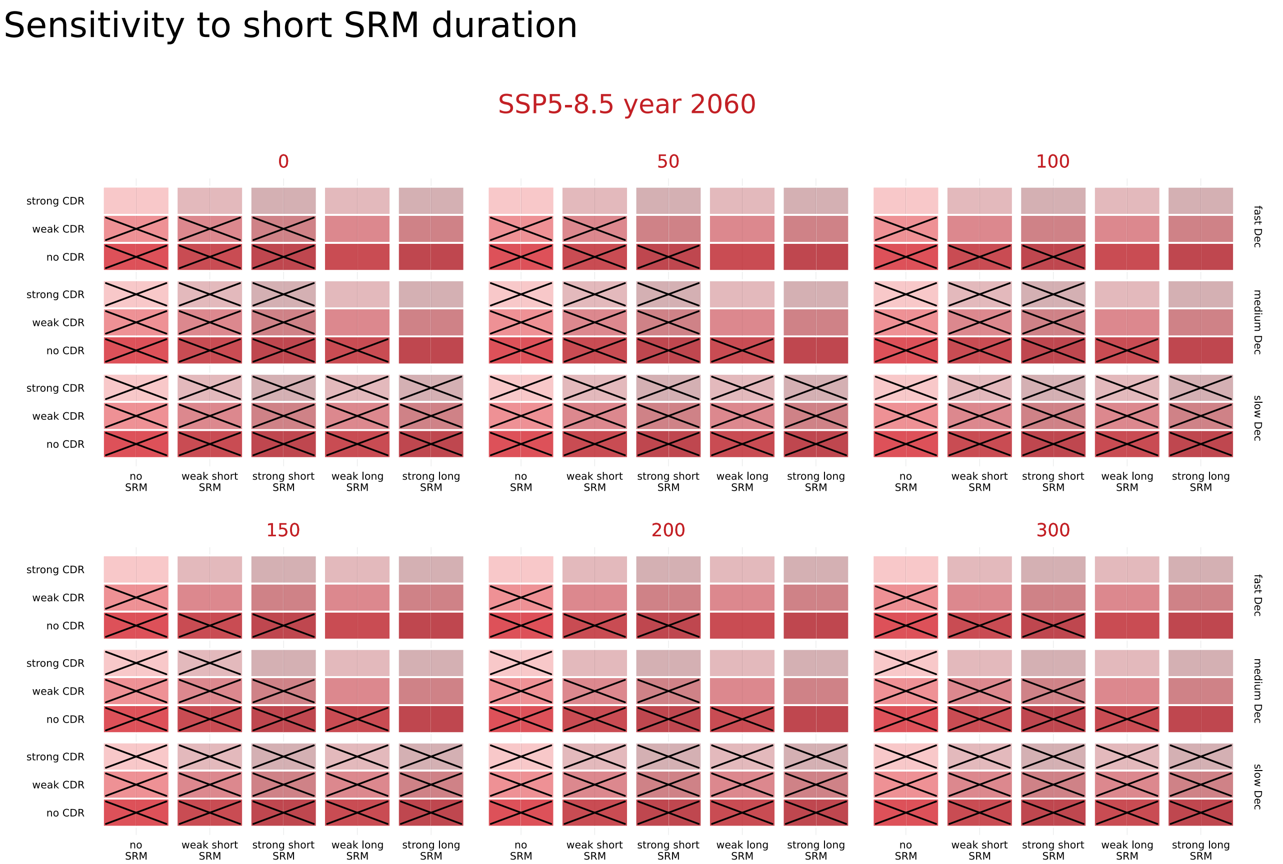

Figure C8. Sensitivity of available options to *short SRM* duration for SSP5-8.5 in year 2060. The numbers indicate the years of continued SRM after decarbonisation has finished. Only the columns corresponding to *short SRM* are subject to change.

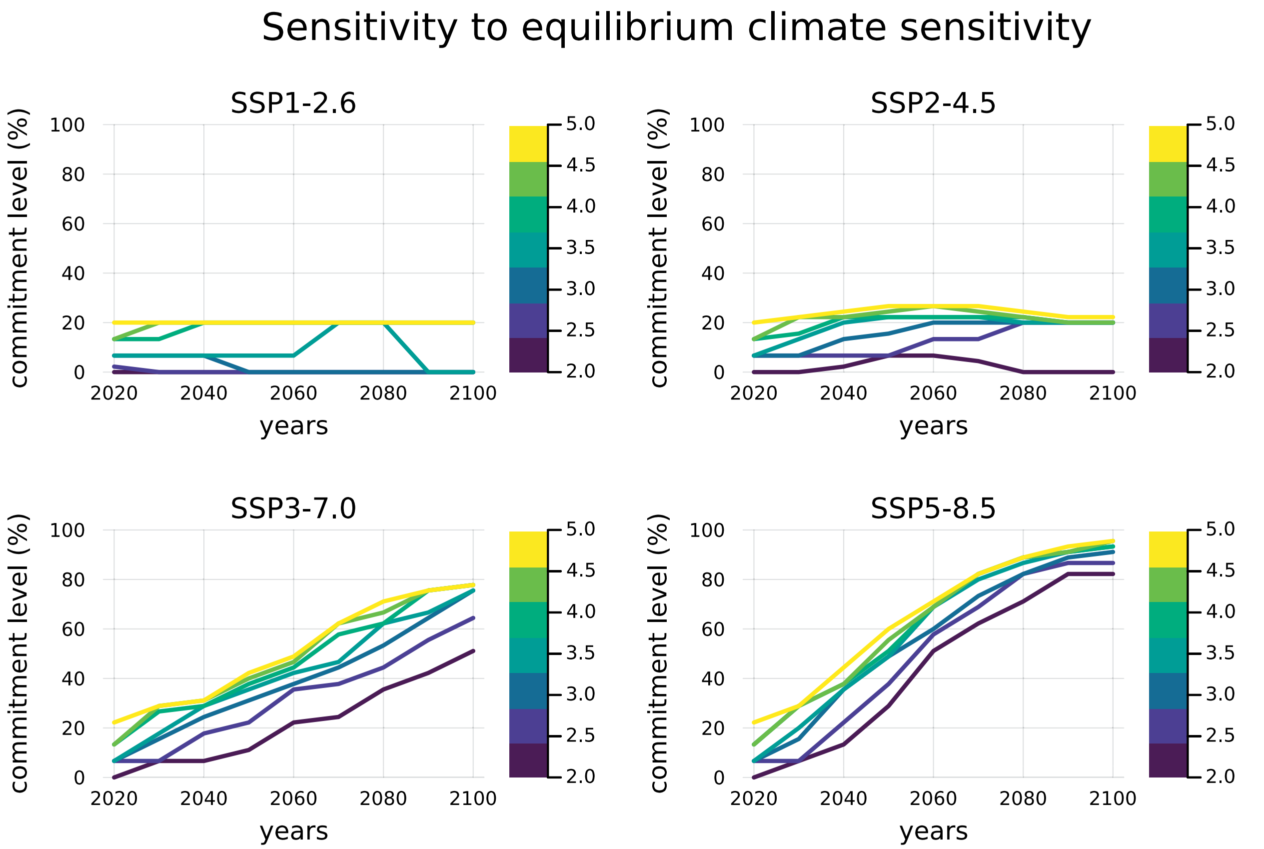

Figure C9. Sensitivity of commitment level to equilibrium climate sensitivity in the SURFER model. Commitment level for states along the different SSP scenarios (as top panel of Fig. 2, y-axis inverted). Each panel corresponds to a different SSP scenario. Each line, within each panel, corresponds to the commitment assessment for a different equilibrium climate sensitivity where the line color encodes the value used (see side color bar). 7 equispaced values of climate sensitivity have been considered between 2 and 5°C. The time horizon has been fixed at 2000 years. The units of the color bar are °C.

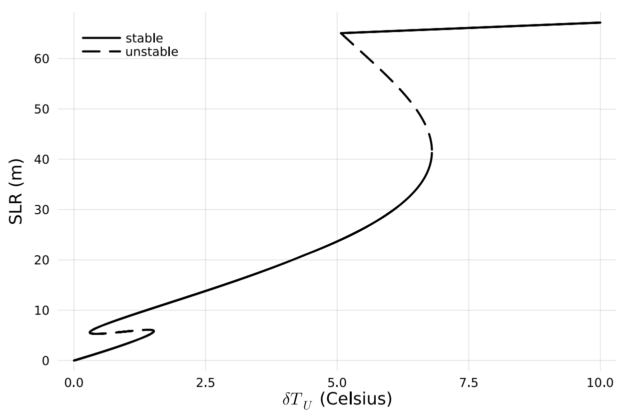

Figure C10. Sea level rise bifurcation diagram for the SURFER model.

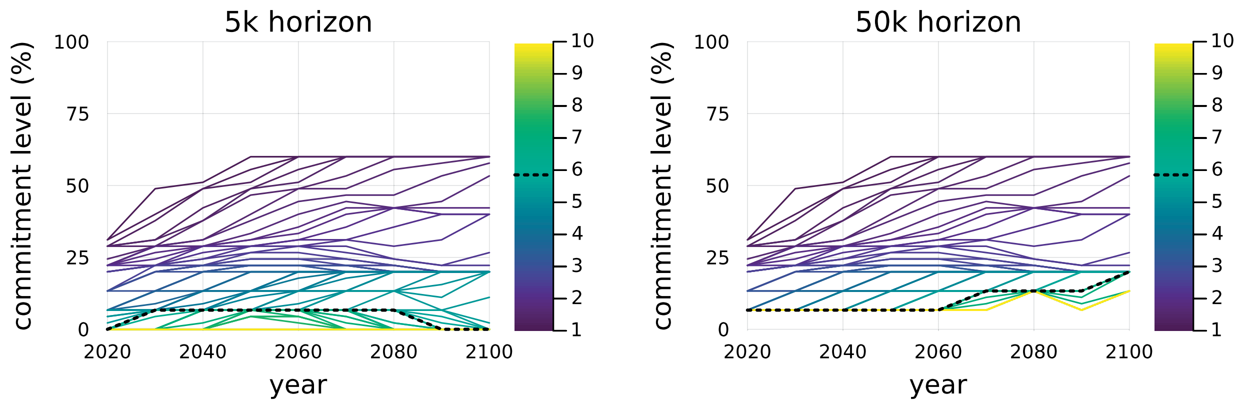

Figure C11. Sensitivity of commitment level to sea level rise target for SSP2-4.5 and two different time horizons of 5000 and 50 000 years. Commitment level for states along the SSP2-4.5 (as top panel of Fig. 2, y-axis inverted). Each panel corresponds to a different time horizon. Each line, within each panel, corresponds to the commitment assessment for a different sea level rise target, as in Fig. C2, where the line color encodes the target used in meters (see side color bar). Targets have been considered in the range between 1 to 10 meters. Dashed black line corresponds to the SLR target coinciding with the SLR bifurcation point around 1.5°C, see Fig. C10.

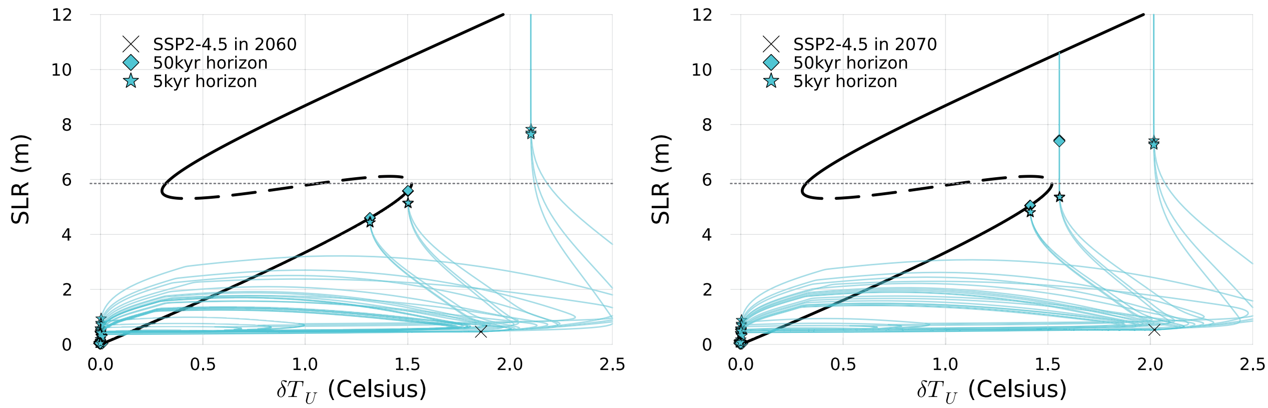

Figure C12. Trajectories corresponding to the different long-term scenarios starting from SSP2-4.5 at 2060 (left) and 2070 (right), in light blue. Thick black lines correspond to the SLR steady states of the SURFER model. The x marker indicates the initial state, the star and diamond markers the position in phase space after 5kyr and 50kyr respectively.

to Greenland's tipping point. We also see that both horizons lead to identical commitment levels when the targets are small enough (from 1 m to 5 m approx.) and that they differ for targets slightly smaller than ∼ 5.9 m to 10 m.

For the 50 k horizon with target ∼ 5.9 m there are increases in the commitment level for the state from 2060 to 2070 and 2090 to 2100. These increases in commitment level happen because a group of options that end on the lower SLR branch of the bifurcation diagram for the lower committed state (e.g. SSP2-4.5 at 2060), end on the higher SLR branch for the consecutive state (in this case, SSP2-4.5 at 2070), this can be seen in Fig. C12. When this happens the trajectories associated with those lost options pass very close to the ice sheet bifurcation point in phase space. The dynamics close to a bifurcation point tend to be very slow, and a time horizon of 5kyr is not enough to appreciate the committed SLR. We put time markers in Fig. C12 to make this point and help understand the sensitivity shown on Fig. C11. We conclude that very large time horizons, together with appropriate targets, are needed for slow tipping behaviour to be apparent in the lost options commitment assessment. This is because the already slow ice sheet dynamics slow down even more close to bifurcation points. We have shown that even when considering very long horizons, the impact of ice sheet tipping points on lost options commitment assessment isn't big. The increases seen in commitment level in Fig. C11 for bigger targets and 50k horizon is of the same order than the ones corresponding to other targets and timescales. Additionally, SURFER v.2.0 does not include sediment dynamics related to carbonate dissolution and silicate weathering, which determine the fate of fossil fuels at time scales beyond several millennia. Those additional processes act as CO_2 sinks and have the potential of lowering the commitment level on assessments with such long horizons, making it even harder for ice sheet tipping points to show up as commitment level tipping points in such lost options commitment assessments.