

Faculté des sciences

Estimation of the safe operating space with a probabilistic assessment of future regional temperatures, based on the notion of lost options commitment.

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Abstract

The safe operating space expresses the idea that there is a boundary that humanity should not exceed in order not to compromise the favourable conditions in which it has been able to develop. The lost options commitment measures the number of policy options, out of a predetermined set of options, which result in transgressing a predetermined ethical state. In this work, we combine the two notions to determine which policy options result in transgressing the safe operating space. The boundary of the safe operating space is simplified: the limit is set at 35°C mean annual temperature. Our study uses as climate target exceeding an average annual temperature of 35°C in one region of the world within a time horizon of 2000 years and a set of 9 long-term scenarios as possible options. To achieve this, the SURFER and MESMER models are combined. SURFER models global warming curves up to the year 4000. MESMER adds noise to these curves and produces temperature distribution maps for each year. Analysis of the results shows that some scenarios are safe, while others are not. The longer we wait to make a commitment, the more future generations lose options. The longer we wait before drastic reductions in emissions, the more we commit future generations to using technologies that do not exist, yet. The regions most often at risk are Western Africa, the Arabian Peninsula, India and the Amazon rainforest. When the limit is set at 30°C rather than 35°C, more options are lost. The work also shows the contribution of stochastic rather than deterministic trajectories. However, given the inherent complexity of the climate system, the uncertainties associated with climate models and some decisions relating to the work method, these results must be interpreted with caution.

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List of acronyms and abbreviations

Regions of the world

ARP	Arabian Peninsula
CAF	Central Africa
CAR	Caribbean
CAU	Central Australia
CNA	Central North America
EAS	East Asia
EAU	Eastern Australia
ECA	East Central Asia
EEU	Eastern Europe
ENA	Eastern North America
ESAF	East Southern Africa
ESB	East Siberia
GIC	Greenland/Iceland
MDG	Madagascar
MED	Mediterranean
NAU	Northern Australia
NCA	Northern Central America
NEAF	North Eastern Africa
NEN	North-Eastern North America
NES	North-Eastern South America

NEU	Northern Europe
NSA	Northern South America
NWN	North-Western North America
NWS	North-Western South America
NZ	New Zealand
RAR	Russian Arctic
RFE	Russian Far East
SAH	Sahara
SAM	South American Monsoon
SAS	South Asia
SAU	Southern Australia
SCA	Southern Central America
SEA	South East Asia
SEAF	South Eastern Africa
SES	South-Eastern South America
SSA	Southern South America
SWS	South-Western South America
TIB	Tibetan Plateau
WAF	Western Africa
WCA	West Central Asia
WCE	Western and Central Europe
WNA	Western North America
WSAF	West Southern Africa
WSB	West Siberia

Other acronyms and abbreviations

AOD	aerosol optical depth
AR	autoregressive
CDR	carbon dioxide removal
CFC	Chlorofluorocarbons
DDT	Dichlorodiphenyltrichloroethane
Dec	decarbonisation
DU	Dobson unit
E/MSY	extinctions per million species-year
GDP	gross domestic product
HANPP	human appropriation of the biosphere's net primary production
ITCZ	Intertropical Convergence Zone
IUGS	International Union of Geological Sciences
MAT	mean annual temperature
MAUP	modifiable areal unit problem
MESMER	Modular Earth System Model Emulator with spatially Resolved output
NPP	net primary production
SCC	social cost of carbon
SDG	Sustainable Development Goal
SRM	solar radiation modification
SSP	Shared Socioeconomic Pathway
SURFER	Sea level Uprise Response under Forcings of Emissions and solar Radiation modification
WBT	wet-bulb temperature

Chapter 1

Introduction

In the late 1950's, Rachel Carson began working on different environmental problems she believed were caused by pesticides. She found that the overuse of several synthetic pesticides was responsible for the poisoning of soils, water and entire ecosystems in the United States of America. The effects on human health, animals and crops were experienced over several years. Her research led to the publication of her famous book *Silent Spring* in 1962 (Carson Rachel, 1962). This book raised public awareness of environmental issues, led to the banning of DDT for agricultural use and inspired the creation of the U.S. Environmental Protection Agency. Finally, her work was also the first in a long series describing the limits of our actions on the environment: our decisions have an impact on the environment which can lead us to an unwanted state. This is represented by the planetary boundaries.

When you think of planetary boundaries, the safe operating space springs to mind. The notion was developed by Johan Rockström in 2009 (Rockström et al., 2009) and it provides a theoretical framework which includes the planetary boundaries. The safe operating space expresses the idea that there is a boundary that humanity should not exceed in order not to compromise the favourable conditions in which it has been able to develop. Within this boundary, we are in operating space and the development of the society is safe. When the boundary is crossed, societies are unsustainable: we are destroying our environment and the conditions in which we can thrive. Nine planetary boundaries were originally identified: climate change, biosphere integrity, land system change, freshwater change, biogeochemical flows, novel entities, stratospheric ozone depletion, atmospheric aerosol loading and ocean acidification. According to the most recent papers, the first six of these are crossed (Richardson et al., 2023).

More recently in Martínez Montero et al., 2024, the objective was to establish which decisions had the effect of leading us into an unwanted state. The article introduces the notion of "lost options commitment" to quantify how the scope of future generations to avoid harmful long-term futures narrows down. It measures the number of policy options, out of a predetermined set of options, which result in transgressing a predetermined ethical state. The predetermined ethical state in the article is a 3-metre rise in sea level.

The set of option includes more-or-less rapid decarbonisation, carbon dioxide removal and solar radiation modification. The Martínez Montero et al., 2024 paper is a proof-of-concept, and it may naturally involve more complex specification of the unwanted state, involving other variables and policy options.

In the present work, the safe operating space framework and the lost options commitment metric are combined to determine the range of decisions our society can make to remain in the safe space. We use the framework of the study of Martínez Montero et al., 2024 except that instead of sea level, temperature is used to define the unwanted state. In this case, we assume that the target of staying below planetary boundaries can be simplified to a target of not exceeding a temperature of 35°C (or 30°C in another experiment). Furthermore, the unwanted state is analysed regionally and not globally as in Mares and Moffett, 2016. Only the decarbonisation and carbon dioxide removal options are analysed here (solar radiation modification options are not included). Finally, we add a stochastic component to the analysis to reflect the random nature of atmospheric dynamics. We ask: what does the safe operating space look like when we explore different degrees of political commitments? What is the effect of the choice of criterion defining the unwanted state? What is the effect of changing the number of realisations? What is the effect of adding the stochastic process? How does the unwanted state apply spatially?

According to Rockström, Johan, 2021 finding the boundaries of the safe operating space is like searching the corners of a room by not getting close to them. The present work makes it possible to establish which, of an array of possible decisions, result in a risk of an average annual temperature of over 35°C in a given area of the world. Not only does it shed light on our present and future range of action, it also allows us to establish the urgency of the situation and which decisions are dead ends.

This work consists of four sections. The first section is a review of the literature. The aim is to examine the scientific context and the major advances that have led to the conception of the safe operating space. Secondly, the various applications of the safe operating space and the definition criteria considered in the literature are reviewed. The second section details the development of the method and an explanation of the two models used: SURFER and MESMER. The third section presents the results and the sensitivity analysis. The final section discusses the method and results. Suggestions for improvement are given, as well as the strengths and weaknesses of the study.

Chapter 2

Literature Review

2.1 Limits to growth

The Holocene is a Quaternary interglacial period covering the last 11,700 years, which is still ongoing. It is a temperate period that follows the last ice age of the Pleistocene. It is characterised by relative stability and warm planetary conditions (Petit et al., 1999). This climate stability can be explained by a relatively constant level of greenhouse gases until the XIXth century, stable ice caps and the absence of cataclysmic events. These stable conditions could explain the development of agriculture (Gupta et al., 2006), which is one of the elements that have led to the development of civilisations. There is no evidence that humans can survive other climatic conditions. That is why it's important to preserve them so that we can continue to thrive.

After World War Two, a *Great Acceleration* has characterised a number of variables intrinsic to our societies, pushing the Earth system to its limits. The first time the term *Great Acceleration* is used was in 2005, in an article (Hibbard et al., 2006), highlighting a series of graphs showing the increase in 12 Earth system indicators and 12 socio-economic indicators (Steffen et al., 2004) (Figure 1). Since the industrial revolution, indicators such as population, real GDP, foreign direct investments, urban population, primary energy use, fertiliser consumption, greenhouse gases, surface temperature, ocean acidification, marine fish capture, tropical forest loss, terrestrial biosphere degradation and others have seen their growth accelerate. Although the authors expected to see an increase since 1950, they were surprised to see how important the phenomenon was.

The concept of Great Acceleration is closely linked to that of the Anthropocene. It is estimated that since the Industrial Revolution, humanity has shifted the Earth system out of the Holocene period of relative stability. We are now entering the Anthropocene era, with the idea that human activities are driving changes as much as other forcings active at the geological scale. The Anthropocene is understood to be the age of irreversible human impacts on the planet (Witze, 2024b). It has therefore been proposed to define a new geological epoch to mark this transition. The year 1952 has been proposed as the starting year in reference to the nuclear deposits accumulated since 1952 in Crawford Lake

(Witze, 2024a). After years of debate, the IUGS has decided to define the Anthropocene by reference to the strict standards. Yet, the word can and will continue to be used: it is already well established in our lexicons and it effectively reflects a reality in ecology, anthropology and other disciplines that try to capture the human influence in a simple concept. Not everyone agrees on the start of the Anthropocene: for some it began 10,000 years ago, for others 1952 is the beginning of the period (Ruddiman, 2018). Not everyone agrees on the designation: some suggest that the Anthropocene is a geological event rather than an epoch (Witze, 2024a). Despite this, there is some agreement that the limits of the Earth system have been reached because of our activity.

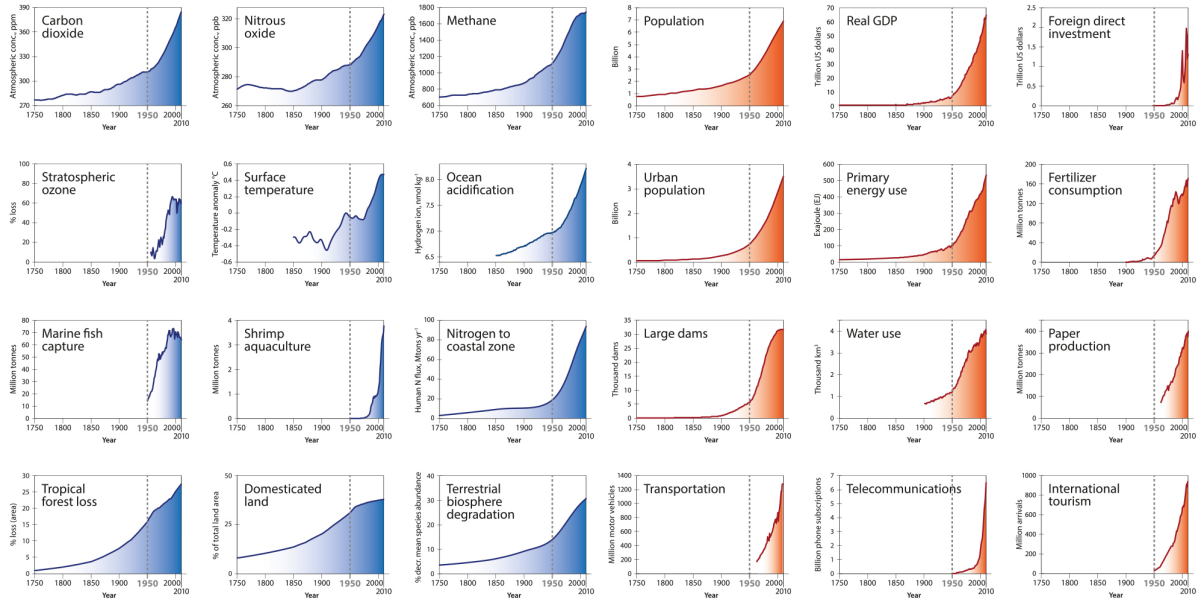


Figure 1: Trends from 1750 to 2010 in globally aggregated indicators for the structure and functioning of the Earth System in blue and for socio-economic development in red (Steffen, Broadgate, et al., 2015).

In 1972, the relationship between planetary limits and human activity is clearly established in a report called "The Limits to Growth", also known as "The Report of the Club of Rome" or "Meadows Report" (Meadows et al., 1972). The report aimed at assessing the consequences of demographic and economic growth on the state of the world's natural resources. It uses the "world3" model to explore different scenarios for economic and environmental change. This is the first model to explore future scenarios, taking into account population growth, fertility, mortality, industrial production, food and large-scale pollution. The report highlights that it is impossible to have infinite economic and demographic growth in a world with limited resources. Indeed, the only scenarios envisaged that do not result in a collapse are those in which exponential growth is halted.

The report on the limits to growth opened the door to another report, published in 1987, which laid the foundations for sustainable development. This was the Brundtland report commonly known as "Our Common Future" (World Commission on Environment and Development, 1987). Sustainable development is defined as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". With this latest report, not only are the limits taken into account, but also the importance of enabling future generations to avoid crossing them. It is in this context that the concept of a safe operating space emerges.

2.2 A safe operating space

In 2009, Johan Rockström and his colleagues developed the concept of the safe operating space (Rockström et al., 2009). There is a space of states delimited by planetary boundaries in which humanity can develop without destroying the environment. Crossing these thresholds could have important consequences for humanity because they're fundamental to ensure the planet's resilience for remaining in a Holocene-like state (Raworth, 2013). When we talk about the planet's resilience, we mean the capacity of the Earth system to return rapidly to its initial state after a disturbance. What we mean by safe is a safe distance from unknown conditions. It took several years to assess the boundaries and which ones are crossed. The boundaries are defined by reference to the planet's biophysical subsystems or processes such as climate change, biosphere integrity, land system change, freshwater change, biogeochemical flows, novel entities (defined below), stratospheric ozone depletion, atmospheric aerosol loading and ocean acidification (see Figure 2). In the latest update of the state of the safe operating space, all boundaries are quantified and six of them appear to be transgressed (Richardson et al., 2023).

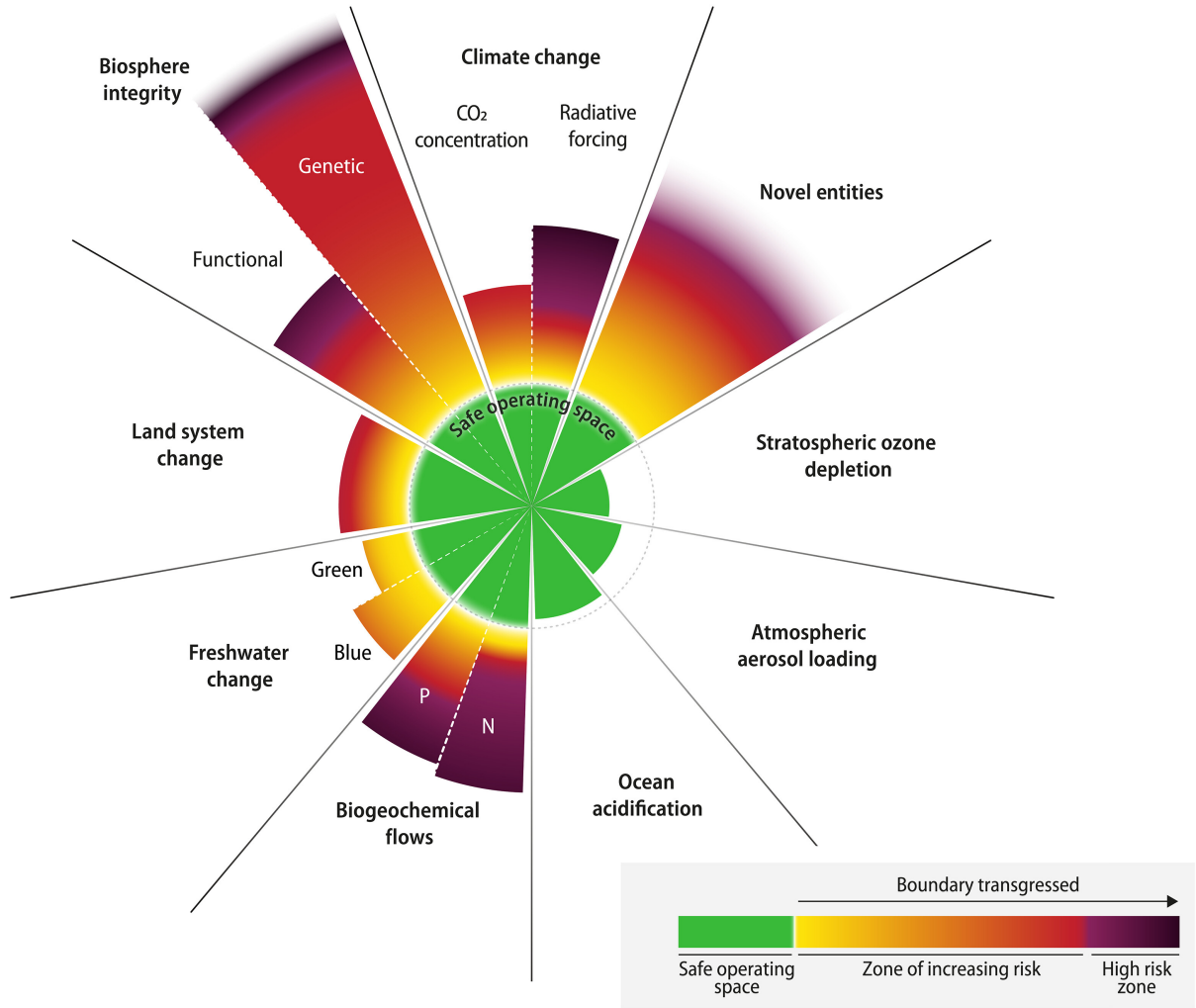


Figure 2: Planetary boundaries (Richardson et al., 2023).

Specifically, for each boundary, it is possible to tell whether it is in the safe operating space, in a zone of uncertainty or in a dangerous level (Steffen, Richardson, et al., 2015). The only boundaries that are not transgressed are stratospheric ozone depletion, atmospheric aerosol loading and ocean acidification, although the latter is very close to be. Of the other six boundaries: climate change, biosphere integrity, biogeochemical flows and novel entities are in the high risk zone, while land system change and freshwater change are in the zone of increasing risk. Each of these boundaries is characterised by a proxy variable called control variable which can be measured. In Richardson et al., 2023, a maximum and a current value of the control variables are given. The next section is a description of those.

2.2.1 Planetary boundaries description

The control variables of the climate change boundary are atmospheric CO_2 concentration and total anthropogenic radiative forcing at the top of the atmosphere. For the first variable, the boundary is 350 ppm. In 2022, the concentration was 417 ppm (Forster et al., 2023). For the second variable, the boundary is $+1W/m^2$. In 2022, the radiative forcing was estimated to be $+2.91W/m^2$ relative to 1750 (Forster et al., 2023). The two planetary boundary values correspond more or less to a warming of $+1.5^\circ C$, consistent with the objectives of the United Nations Paris Climate Agreement.

The change in biodiversity boundary is divided between two control variables: genetic diversity and functional integrity. The planetary boundary for change in genetic diversity is defined as the maximum extinction rate compatible with preserving the genetic basis of the biosphere’s ecological complexity (Rockström et al., 2009). To remain in the safe operating space, we should have a rate of extinction loss of less than 10 E/MSY (extinctions per million species-years) (Richardson et al., 2023). The current value of the control variable is more than 100 E/MSY (Ceballos et al., 2015; Rounsevell et al., 2020; Cowie et al., 2022). The functional component of the biosphere integrity boundary is defined as a limit to the human appropriation of the biosphere’s net primary production (Richardson et al., 2023). We should have a HANPP (human appropriation of the biosphere’s net primary production) of less than 10% of preindustrial Holocene NPP (net primary production). The current value is 30% HANPP (Richardson et al., 2023).

The boundary of stratospheric ozone depletion is measured by the global average stratospheric ozone concentration. It is set at 276 DU. Smaller concentrations correspond to a hole in the ozone layer. This is why values higher than 276 DU are desired. The current value of the control variable is 284.6 DU (Richardson et al., 2023). This is the frontier of the safe operating space from which we are furthest away. There was a time when this value was lower because of our CFC production, but since the signing of the Montreal Protocol in 1987, the situation has improved (Richardson et al., 2023). However, the ozone depletion boundary is currently crossed over Antarctica and the high southern latitudes, and only during the three months of the southern spring (Pazmiño et al., 2018).

Ocean acidification is caused by anthropogenic carbon emissions and is responsible for the weakening of many marine ecosystems. In this case, the control variable is given by the average global surface ocean saturation state with respect to aragonite (Ω_{arag}). Aragonite minerals are forms of calcium carbonate used by many marine organisms to build their shells and skeletons. Aragonite saturation is an indicator of the seawater’s

ability to support biological calcification. If saturation decreases, the situation becomes problematic for these organisms. The ocean acidification boundary is set at $2.75 \Omega_{arag}$, i.e. 80% of $3.44 \Omega_{arag}$ which is the pre-industrial level (Richardson et al., 2023). The current value of the control variable is equal to $2.8 \Omega_{arag}$, i.e. between $3.44 \Omega_{arag}$ and $2.75 \Omega_{arag}$, but very close to the risk zone (Jiang et al., 2015).

To remain in the safe operating space, we must not disturb certain biogeochemical flows too much. These flows are the phosphorus (P) and nitrogen (N) cycles. The global boundary for P is a sustained flow of $11 \text{ Tg of P } year^{-1}$ from fresh water to the ocean, to avoid large-scale anoxia (Steffen, Richardson, et al., 2015). The most recent value is $22 \text{ Tg of P } year^{-1}$ (Carpenter and Bennett, 2011). The regional level boundary is set at a flow of $6.2 \text{ Tg of P } year^{-1}$ from fertilisers to erodible soils, to avert widespread eutrophication of fresh water ecosystems (Richardson et al., 2023). The most recent value is $17.5 \text{ Tg of P } year^{-1}$ (Lu and Tian, 2017). The planetary boundary for N is the application rate of intentionally fixed N to the agricultural system of $62 \text{ Tg of N } year^{-1}$ (Steffen, Richardson, et al., 2015). For now the value of the control variable is estimated to be $190 \text{ Tg of N } year^{-1}$ (Richardson et al., 2023).

The land system change boundary focuses on three biomes: tropical, temperate and boreal. It is measured by the percentage of original forest still covered by forested land. The global planetary boundary is set at 75%. It is crossed since the current value is approximately 60% (Richardson et al., 2023).

The freshwater change boundary reflects changes across the entire water cycle over land due to human modification. The boundary is composed of changes in blue water (surface and ground water) and changes in green water (plant available water). Control variables are defined as the percentage of annual global ice-free land area with stream-flow/root zone soil moisture deviations from preindustrial variability (Richardson et al., 2023). Boundaries are set at the 95th percentile of preindustrial variability, i.e. variability of the percentage of global land area with deviations. It equals 10.2% for blue water and 11.1% for greenwater. The current values of control variables are: 18.2% (bluewater) and 15.8% (greenwater) (Porkka et al., 2022).

Atmospheric aerosol loading has increased because of human activity (Carslaw et al., 2017). This increase can affect monsoon system such as West African monsoon (Haywood et al., 2013) and Indian monsoon (Krishnamohan and Bala, 2022; Roose et al., 2023). The control variable is the interhemispheric difference in aerosol optical depth (AOD).

It can, for example, shift the location of the Intertropical Convergence Zone (ITCZ) (Donohoe et al., 2013). The AOD is an integrated measure of the overall reduction in sunlight reaching Earth's surface caused by all absorption and scattering in the vertical air column (Richardson et al., 2023). The planetary boundary is set at 0.1 (mean annual interhemispheric difference) (Richardson et al., 2023). The current value is estimated to be 0.076 (Chin et al., 2014; Zanis et al., 2020; Vogel et al., 2022).

The last boundary is about novel entities which are synthetic chemicals and substances; anthropogenically mobilized radioactive materials, including nuclear waste and nuclear weapons; and human modification of evolution, genetically modified organisms and other direct human interventions in evolutionary processes (Richardson et al., 2023). The planetary boundary is set at 0% release of untested synthetic materials into the Earth system, which is certainly not the case at the moment.

2.2.2 A safe and just operating space

While the safe operating space is designed to deal with planetary boundaries, an initiative aims at defining a "safe and just" operating space, with the inclusion of a social foundation. It was developed in 2012 by the economist Kate Raworth to find a path towards sustainable development (Raworth, 2012). The beginning of her thinking was marked by the realisation that GDP is no longer a good indicator of the development of society, because it ignores the damage caused to the planet or to human beings. GDP is only an indicator of economic development. In her view, the safe operating space as conceptualised by Rockström is a better compass for moving our societies forward, but it needs a social dimension. The safe and just operating space is the space between the ecological ceiling — or the planetary boundaries — and the social foundation (see Figure 3). This space takes the shape of a doughnut, hence the name *Doughnut Theory*. Safety is referring to the stability of the Earth system and justice, with meeting human needs and reducing exposure to risks (Rockström et al., 2021).

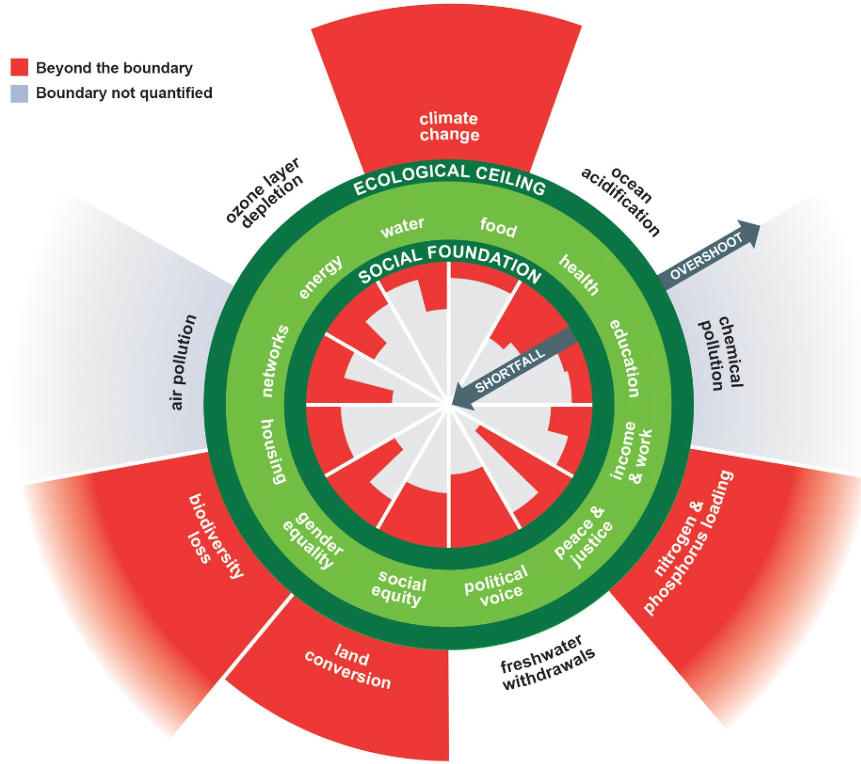


Figure 3: The safe and just operating space (Raworth, 2017).

The twelve dimensions of the social foundation are derived from the Sustainable Development Goals (Raworth, 2017). It should be noted that just because decisions move away from planetary boundaries and back into the safe operating space does not mean that they move away from the social foundation (Oliver et al., 2022). Conversely, crossing a planetary boundary can exacerbate poverty in some regions of the world (Raworth, 2012).

2.3 Safe operating space applications

The previous sections have established that humanity is causing a change in the state of the Earth system that is taking us out of the Holocene. The safe operating space provides us with a framework for studying this issue. Since its conception, the safe operating space has been used extensively for research, policymaking and planning. Yet, some features have been adapted. For example, criteria other than those used for planetary boundaries are being considered. Finally, the question arises as to which scenarios and which political commitments will take us out of the safe operating space. We now review some of the applications of safe operating space.

2.3.1 Definition of a limit

Defining an ethical target is no easy task. It involves choosing a general criterion and finding a justification for it. In the case of the safe operating space, the boundaries are defined in relation to the Holocene, but it could be argued that we can find ourselves in an unwanted state before leaving it. For example, one criterion might be to avoid crossing a tipping point. A tipping point is "an abrupt climate change occurring when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause and with a degree of irreversibility" (Lenton et al., 2008). Examples of tipping points are associated with the Amazon rainforest, the Indian monsoon, the permafrost, the Atlantic thermohaline circulation and the ice caps. But it is possible to find yourself in an unwanted state long before you cross these tipping points.

This explains the search for other criteria for limits or boundaries. Tipping point or not, the definition of 'safe' implies a measurement of impact and ethical judgements about what is desirable and what is not. Kate Raworth's work is a good example of this. But there are also the Sustainable Development Goals (SDG), which aim to reach a state rather than maintaining one. Other studies focus more on climate limits with a direct impact on the human population, such as heat waves, river floods, droughts and crop failures (Thiery et al., 2021), sea level rise (Martínez Montero et al., 2024) or the rate at which the change occurs (Nordhaus, 2017).

One of these criteria is linked to the human climatic niche. Humans, like all other animals, live in an environmental niche. It is estimated that this niche is characterised by a major mode around 11°C to 15°C mean annual temperature (MAT) (Xu et al., 2020). The wet bulb temperature (WBT) can also be used as an indicator of the state of the climatic niche (Lenton et al., 2023). A wet bulb temperature higher than 28°C reduces the effectiveness of the cooling produced by sweating, and a wet bulb temperature higher than 35°C can be fatal (Sherwood and Huber, 2010; Raymond et al., 2020). Lenton et al., 2023 explain that "high temperatures have been linked to increased mortality (Mora et al., 2017; Parncutt, 2019), decreased labour productivity (Parsons et al., 2022), decreased cognitive performance (Masuda et al., 2020), impaired learning (Park et al., 2021), adverse pregnancy outcomes (Chersich et al., 2020), decreased crop yield potential (Watts et al., 2021), increased conflict (Hsiang et al., 2011; Hsiang et al., 2013; Mares and Moffett, 2016), hate speech (Stechemesser et al., 2022), migration (Mueller et al., 2014) and infectious disease spread (Watts et al., 2021; Carlson et al., 2022)".

2.3.2 Different scenarios

The previous section reviewed some of the criteria that can help us define a limit. In order to analyse the possibility of crossing this limit, several scenarios are considered. The aim of this section is to present the scenarios usually used in global warming studies, i.e. the Shared Socioeconomic Pathway (SSPs). We also discuss the predictability of the climatic trajectories resulting from these pathways.

SSPs are defined as "reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies" (O'Neill et al., 2014). The aim of the SSPs is to present narratives relating to the impact, adaptation and mitigation resulting from global warming until 2100. Based on the outcomes of interest for climate change, it is possible to identify combinations of key socioeconomic drivers that are likely to produce those outcomes (O'Neill et al., 2014).

The SSP1 is based on sustainability and is also called *Taking the Green Road*. In this scenario, there are low challenges to mitigation and adaptation in 2100. GDP is no longer the focus of development and is replaced by the pursuit of well-being. Planetary boundaries are respected. The SSP2, also called *Middle of the Road*, has medium challenges to mitigation and adaptation. Societies are moving towards a model that respects planetary boundaries, but too slowly, so that some countries are doing better than others. The SSP3 is based on regional rivalry and is also called *A Rocky Road*. In this scenario, there are high challenges to mitigation and adaptation. Policies focus on security, energy and food security without taking into account the needs of other regions of the world. Material consumption, inequality and environmental degradation persist or worsen. The SSP4 is based on inequality and is also called *A Road Divided*. In this scenario, the mitigation challenges are low thanks to the development of new technologies, but the adaptation challenges are high because this development is occurring at the expense of an improvement in inequalities. The SSP5 is based on fossil-fuelled development and is also called *Taking the Highway*. In this scenario, there are high challenges to mitigation and low challenges to adaptation. Energy consumption linked to fossil fuels is increasing, which allows for innovation and technological and human progress. Lifestyles are energy intensive. Many solutions are being developed to manage social and environmental problems (Riahi et al., 2017).

With these scenarios in mind, it is possible to estimate associated emissions curves on the basis of models (Riahi et al., 2017). It is possible to translate carbon emission curves

into atmospheric carbon concentration curves and determine global warming curves. The resulting radiative forcing in 2100 can then be determined. This is given by a number at the end of each scenario: SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5. Each of these trajectories is deterministic. It is common practice to add noise to these trajectories to make them stochastic, for example by using a first-order autoregressive model (AR1).

2.3.3 Controls and optimal policies

The state of the safe operating space is characterised by its boundaries. We can argue that it can also be characterised by the controls or policies that represent the space for operating (Botta et al., 2017). The more knowledge there is of controls and decisions, the more secure the situation. The only way to know whether our situation is safe is to assess our scope of action. This section presents the literature on these controls.

The policies that are often studied are linked to decarbonisation (Dec), carbon dioxide removal (CDR) or solar radiation modification (SRM) (Seneviratne et al., 2018; Martínez Montero et al., 2024). Decarbonisation aims to reduce carbon-emitting energy consumption. Carbon dioxide removal is a technological process used to capture and sequester atmospheric carbon. Solar radiation modification is a type of geoengineering in which solar radiation is reflected before reaching the Earth’s surface, for example by diffusing aerosols into the stratosphere. Another example of policies studied is the optimal carbon tax (Taconet, 2020).

Initially, it was suggested to think in terms of optimal trajectories for which an economic or social cost is attributed to each tonne of carbon. The social cost of carbon (SCC) gives an indication of the economic cost of an extra tonne of CO_2 emissions into the atmosphere (Nordhaus, 2017). It is then possible to determine which emissions or temperature increases are the most economically optimal. This mode of reasoning implies a great deal of arbitrariness (Keen, 2022). For sequential decision problems, decisions are made at each time step (Botta et al., 2017). It is possible to determine the optimal policy or the one that matters most (Botta et al., 2023). Instead of searching for an optimal trajectory, the lost options commitment metric seeks to quantify the possibility of future generations to alter the trajectory according to criteria that determine an acceptable state (Martínez Montero et al., 2024).

2.4 In summary

To sum up, there is a theoretical framework known as the safe operating space, which can be used to move forward studies on the limits of anthropogenic activities. Although clearly defined, the safe operating space has been redefined using other criteria in more recent studies. This definition requires the choice of a criterion, plausible scenarios for the evolution of society, control scenarios that show the scope of action and a decision model.

Chapter 3

Method

This section describes the choices for defining the safe operating space. The lost options commitment metric is used to reproduce the decision model. The scenarios explored are the four SSPs. The controls considered are decarbonisation and carbon dioxide removal policies. These decisions can be taken every ten years from 2020 to 2100 to extend the possibilities of controls. The chosen criterion of an unwanted state is a mean temperature above 35°C or 30°C.

3.1 Lost options commitment

First of all, we need a specific metric to break out of the theoretical framework of the safe operating space while retaining the simplicity of the concept. This is where the notion of lost options commitment comes in. This is a "a notion that quantifies future generations' scope of action to avoid harmful long-term futures" and it was introduced in Martínez Montero et al., 2024. The paper poses the following question: "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?" (Martínez Montero et al., 2024). Options that cannot meet the climate target are considered *lost*, while those that can, are considered *available*.

This notion can be linked to the concept of sustainable development because it allows us to assess whether future generations have the same scope as we do to meet their needs. The Brundtland Report indeed defines sustainable development as "a development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). The lost options commitment makes it possible to quantify this ability by measuring the consequences of different policy option on the available options to future generations.

The notion of lost options commitment introduces the possibility of putting the safe operating space into practice. Indeed, it is argued that the safe operating space is also characterised by the means we have to remain within its boundaries. These means are

defined as "controls". Specifying these controls is necessary to determine the scope of action available to future generations. It can be assumed that it will be easier to avoid an undesirable state if radical actions are possible. These controls must also be compatible with notions of justice. They must be socially and ethically acceptable.

3.2 Different scenarios

When it comes to projections, we need to explore the many possible futures for our society. This depends on the path our society follows and the choices we make collectively (the controls). The following section puts this framework into context. The first part deals with the choice of controls, while the second one explains the different scenarios of emissions considered.

3.2.1 Controls

In the context of this work, different options for political decision-making are defined. They are based on decarbonisation (Dec) and carbon dioxide removal (CDR) and can be taken every ten years from 2020 to 2100. They are the same as those outlined in Martínez Montero et al., 2024.

Three decarbonisation rates are defined : -0.08 GtC/yr^2 , -0.25 GtC/yr^2 and -0.75 GtC/yr^2 or *slow Dec*, *medium Dec* and *fast Dec*. The medium decarbonisation rate closely matches the decarbonisation rates present in SSP1-2.6. We model decarbonisation options by gradually decreasing emissions at a specified rate until they reach zero. When implemented in a scenario where emissions are already at zero or below, the three decarbonisation options become equivalent and cease to have any impact.

Three carbon dioxide removal rates are defined: 0 GtC/yr , -1 GtC/yr , -2 GtC/yr or *no CDR*, *weak CDR* and *strong CDR*. The strong carbon dioxide removal rate closely matches the one in the SSP1-2.6. We model CDR options by starting since the beginning of the assessment. If decarbonisation remains incomplete for the specific state, there is an immediate decrease in net emissions. CDR persists at a consistent rate after decarbonisation concludes, continuing until atmospheric CO_2 concentration returns to pre-industrial levels. Subsequently, the CDR rate is adjusted to only remove carbon equivalent to what enters the atmosphere from land and ocean sources, maintaining atmospheric concentrations at pre-industrial levels until all reservoirs revert to pre-industrial conditions.

In other words, every ten years, policymakers have the choice of taking a decision on decarbonisation and carbon dioxide removal. We are assuming here that decisions are immediately followed by action, which is far from obvious. This choice is shown in the grid below (Figure 4). The columns correspond to a choice of decarbonisation policy and the rows correspond to a choice of carbon dioxide removal policy. Each box is therefore a choice of policy combination.



Figure 4: The 9 long-term scenarios considered in the lost options commitment assessment

3.2.2 Scenarios

Each of these options is applied to a Shared Socioeconomic Pathway (SSP). We have selected four SSPs : SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5. These trajectories explore the economic, technological and social developments of our societies. The data concerning the different SSPs are based on the SSP database hosted by the IIASA Energy Program.

A total of 324 possible futures are explored: $4 \text{ SSPs} \times 9 \text{ options} \times 9 \text{ years of assessment}$. It is difficult to cover all the possible futures that our societies could follow, but we hope that the 324 trajectories described cover as much of our scope of action as possible. It is important to note that each of these trajectories is characterised by an increase in emissions, which depends solely on the 4 SSPs, followed by their reduction, which depends on the 81 political decisions ($9 \text{ options} \times 9 \text{ years of assessment}$). The diversity of possible futures is therefore rather a diversity of possible futures in terms of emissions mitigation.

3.3 SURFER

The various trajectories are then translated into curves showing changes in the concentration of carbon in the atmosphere. These curves are modelled by the SURFER model and then translated into curves showing changes in the global temperature anomaly, again using the SURFER model.

SURFER stands for Sea level Uprise Response under Forcings of Emissions and solar Radiation modification (Martínez Montero et al., 2022). It is a model of low complexity for carbon-climate dynamics and sea level rise, based on a combination of conservation laws governing atmospheric and oceanic carbon masses, oceanic temperature anomalies, and fit-for-purpose parameterizations for various sea level rise contributors. This model comprises nine loosely coupled ordinary differential equations (ODEs) and describes the carbon fluxes between the following four reservoirs: the atmosphere, the upper ocean, the lower ocean and the soil.

While the model can take anthropogenic CO_2 emissions and the modification of solar radiation by SO_2 injection as external forcings, this work does not exploit the second feature. Furthermore, SURFER is designed to model the responses of the following four variables expressing the forcing: atmospheric carbon concentration, global mean surface temperature, sea level and ocean acidification. This study uses only the first two responses.

The model provides global temperature anomalies for each year from 1765 for the four SSPs and then generates global temperature anomalies for each year from the year of the assessment and for each option until the year 4000. As mentioned above, we have a total of 324 curves showing the evolution of carbon in the atmosphere, and therefore 324 curves showing anomalies in mean global surface temperature, representing as many possible futures. The complete framework of the method is shown in Figure 5.

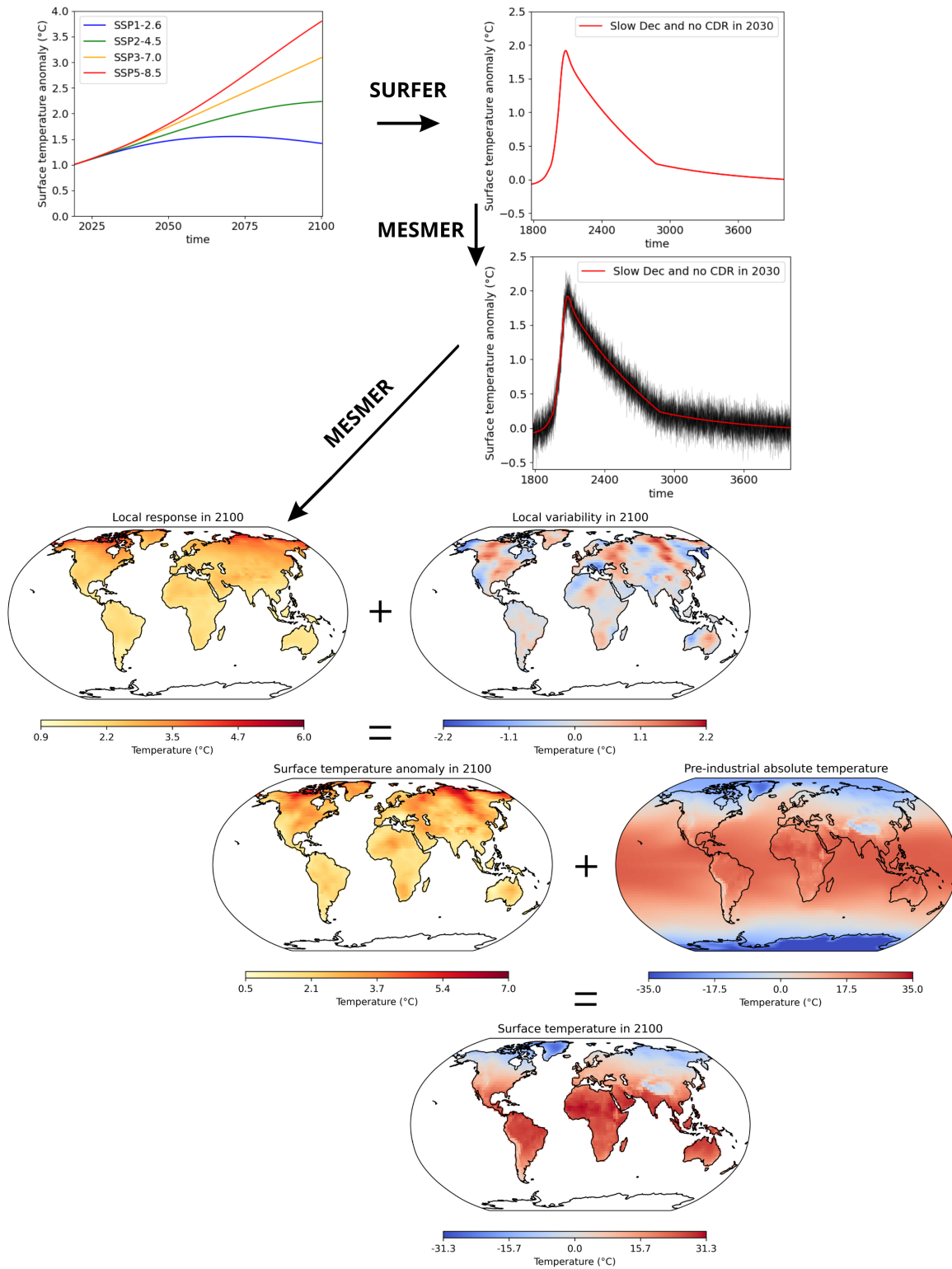


Figure 5: Illustration of the method framework

3.4 MESMER

Once the temperature anomaly curves have been obtained for each possible future, they are used as an input to the MESMER emulator. This step produces surface temperature anomaly maps. It is also possible to create a map of pre-industrial absolute temperatures in order to obtain a prediction of surface temperatures on land.

MESMER stands for Modular Earth System Model Emulator with spatially Resolved output and was introduced in Beusch et al., 2020. This model is used because SURFER is not a spatial emulator and cannot be used to determine the distribution of surface temperatures associated with a given global temperature. The MESMER framework consists of three steps: a global mean temperature module, a local temperature response module and a local residual temperature variability module.

Firstly, MESMER can be used to add global variability to the smooth deterministic curves produced by SURFER. The curves generated with global variability are said to be stochastic. They reflect the random dynamics of the atmosphere and the many possible scenarios. For this research, a dozen stochastic realisations are modelled as an AR process using white noise: those are the distributions of plausible climate states. These curves will enable us to establish a projection with probabilities.

Next, it is possible to generate the local response to the global temperature increase. In concrete terms, this means that it is possible to map the distribution of temperature anomalies for each year and for each realisation. This local response is calculated using linear regression, for which the coefficients are estimated with the ordinary least squares (OLS) method at each grid point.

Finally, the local response would be incomplete without taking the local variability into account. This module takes into account local phenomena such as El Niño. MESMER therefore includes a local residual temperature variability module. This local variability of the residuals is modelled as an autoregressive process of order 1 (AR(1)) with spatially correlated innovations (same as in the global variability module).

The global trend, the global variability, the local response and the local variability of the residuals are combined to obtain a temperature anomaly value for each pixel and time step. As a result, a surface temperature anomaly map of the world is obtained for each year and time step. This temperature anomaly is defined in relation to the pre-industrial level. To obtain the absolute temperatures, we need to generate a map of pre-industrial

temperatures, to which we must add the temperature anomalies obtained in the previous step.

MESMER can also be used to produce this pre-industrial absolute temperature map. Obtaining this map requires several manipulations. The output of MESMER relate to the period from 1850 to 1900, but we have no surface temperature observations dating back to that period. We are therefore going to use an artifice by calling on observations dating from 1901-2020. The average of temperature observations from 1901 to 2020 is calculated. What we call "observations" is in fact a re-analysis produced by ERA5 (Hersbach et al., 2020). Next, the average of the temperature anomalies for this period (calculated by MESMER) is subtracted. Finally, the average of the temperature anomalies from 1850 to 1900 (calculated by MESMER) is added to find the map of average surface temperatures over the period 1850-1900 (Figure 6).

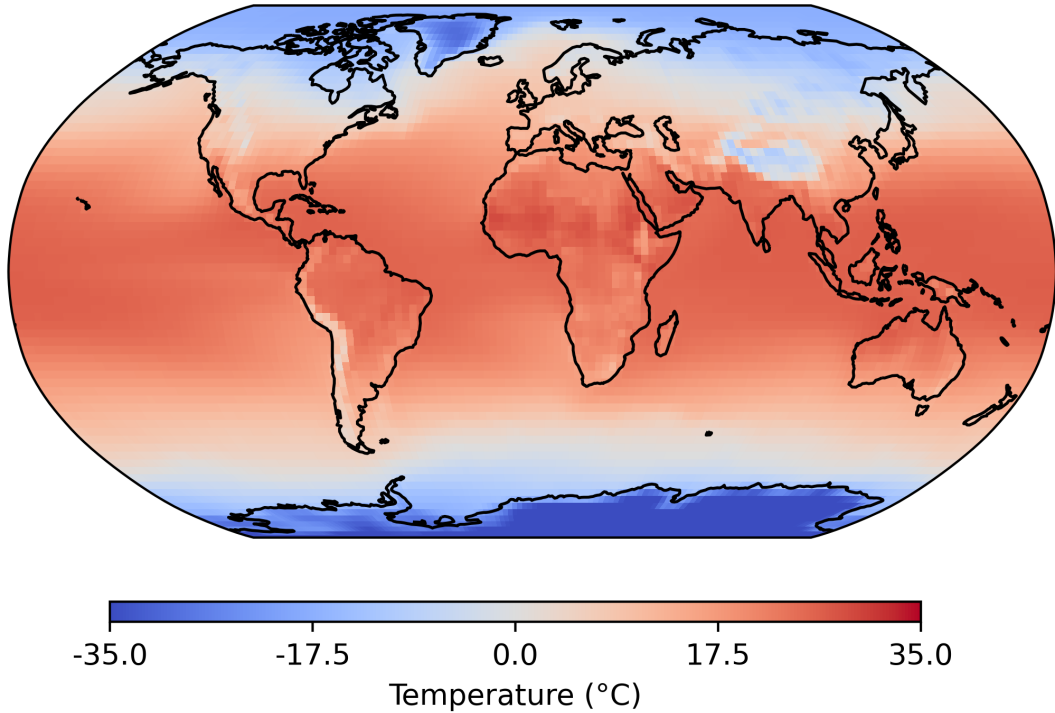


Figure 6: Pre-industrial absolute temperature map calculated with the re-analysis by ERA5.

It is therefore possible to generate, for each year and for each realisation, an absolute temperature map projected into the future by adding this result to the temperature anomaly maps produced in the previous step. The map is composed of 3043 land grid points (2652 when we exclude Antarctica) defined by a $2.5^\circ \times 2.5^\circ$ grid.

3.5 Unwanted state

Finally, we need to establish the boundary defining the "safe zone". We assume that a MAT exceeding 35°C is beyond operation state. As explained in Chapter 2, this criterion can serve as a kind of proxy criterion for the operating space because it provides information on the planetary boundaries that have allowed us to thrive as a species.

We define an option as a lost option when a single inhabited region of the world has its MAT exceeding 35°C in more than one in ten stochastic realisations. This method involves checking the temperature value of the 90th percentile of the achievement distribution year after year. Note that the 90th percentile is always lower than the maximum value of the ten temperatures that will be obtained each year. The average temperature per region is weighted on latitude.

The 44 regions are defined in the sixth Assessment Report of IPCC regions (Iturbide et al., 2020) and are shown in the figure below (Figure 7) with the land grid points considered in grey. Figure 8 is the same as Figure 6 but only for the land grid points considered and the delimitation of regions.

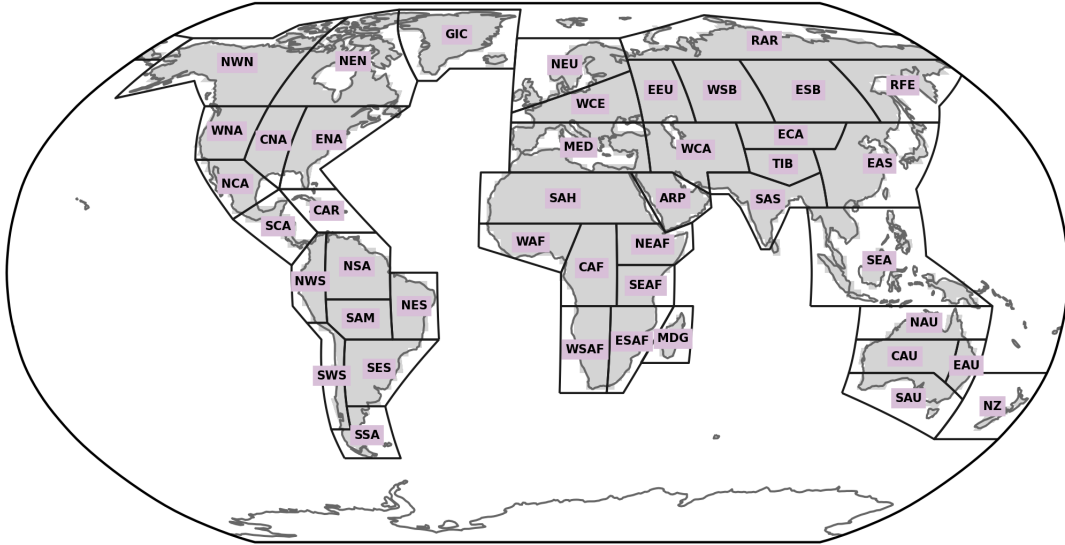


Figure 7: Map of the 44 regions and their abbreviations. The considered land grid points are shown in grey.

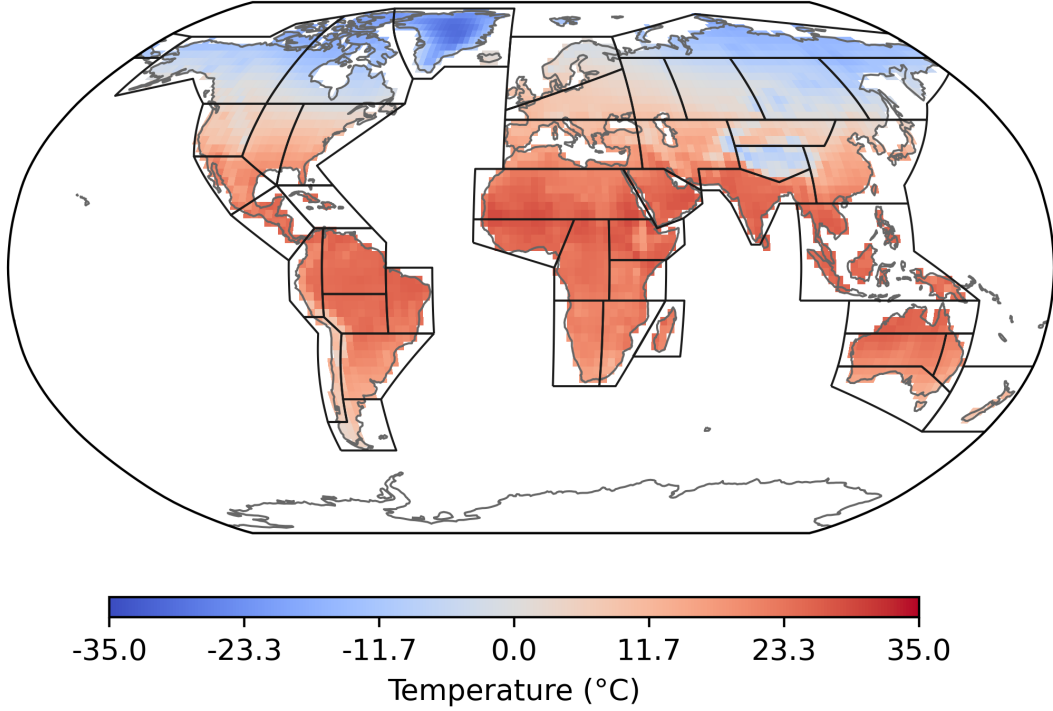


Figure 8: Map of the 44 regions. The colours of the land grid points correspond to the pre-industrial absolute temperature.

3.6 Sensitivity analysis

The sensitivity analysis is an essential part of the robustness assessment of the results. Specifically, we analyse the impact of changing the unwanted state criterion at 30°C rather than 35°C for the same experiment. We also test the consequences of including stochastic variability. First, it is possible to suppress its effect in one of the scenarios. Then, 100 realisations are generated rather than 10 for the same scenario, which allows us to study its influence on the previous conclusions. Note that in this case, the method differs slightly. Rather than checking year by year whether more than 1 in 10 of the events exceeds the undesired state criterion, it is preferable to check, event by event, how many of them exceed the criterion. If the event occurs in more than 10 scenarios, we have a lost option.

Chapter 4

Results

This chapter shows the results and presents the lost options commitment grids. For each SSP, nine grids are presented, corresponding to the nine years of assessment. Each of these grids is similar to the grid shown in Figure 4, which includes the nine options. We mark with a cross the option for which the safe operating space, as defined in this work, is transgressed; this is a lost option. Boxes without a cross indicate an available option. The results of the first experiment are presented in the first section. They are followed by the results of the sensitivity experiments: the sensitivity to temperature criteria, the sensitivity to number of realisations and the sensitivity to the stochastic process.

4.1 First experiment

In the first experiment the unwanted state was specified as annual temperature exceeding 35°C and 10 stochastic realisations were produced. If a region of the world has a MAT that exceeds 35°C in more than one in ten realisations before year 4000 for a given policy, we consider this policy is incompatible with the desired state specification. That option is thus considered to be lost, for that scenario, and at the time of the analysis. The corresponding policy option is then marked by a cross in the box corresponding to the scenario in question. The results are presented for all scenarios, and for the 9 years of assessment from 2020 to 2100 and every ten years in Figure 9.

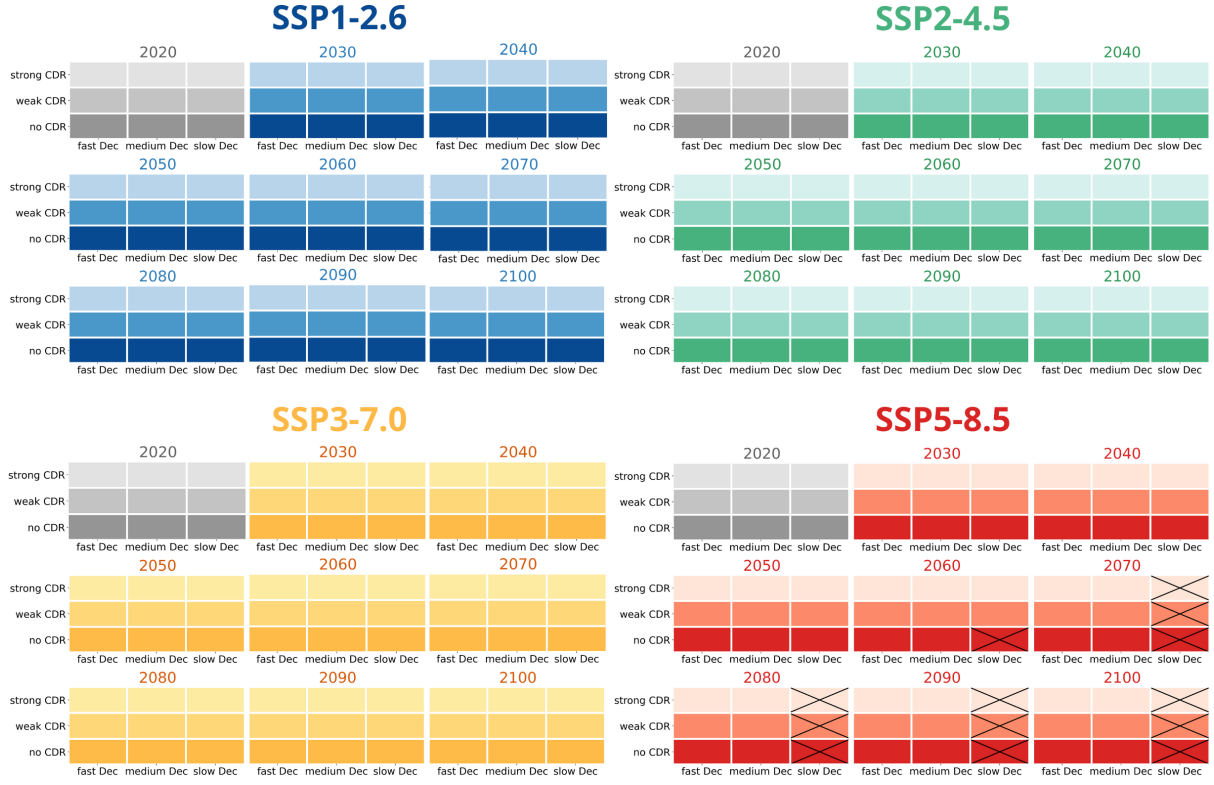


Figure 9: Window of opportunity of the four SSPs in the first experiment. Options that transgress the target are crossed out.

The results of the commitment options that occur for SSP1-2.6 are shown in blue. The results of the SSP2-4.5 are given in green. SSP3-7.0 corresponds to yellow. The colour red is used for the SSP5-8.5. Nine options are tested every ten years for the four scenarios. A scenario's set of available options represents its window of opportunity.

With this model, the 35°C MAT limit appears particularly conservative. Indeed, we see that only 13 options out of the 324 options tested are lost. SSP1-2.6, SSP2-4.5 and SSP3-7.0 are safe. This means that if our societies follow these emissions trajectories, all the options considered in this work are estimated, with this model, to remain in the safe operating space given the unwanted state specified above. Options are only lost if our societies follow the SSP5-8.5 and only for some commitments made after 2050. In 2060, the only option which leaves the safe operating space is the one where we commit to a slow Dec and no CDR option. Conversely, from 2070 onwards, all options that commit to a slow Dec option lead to warming of at least one region of the world by up to 35°C. In other words, if we follow the SSP5-8.5 and we're waiting until 2070 (2080, 2090 or 2100) to commit, only the options based on medium or fast Dec will allow us to remain in the safe operating space.

Again, a box is crossed when a region of the world will see its MAT reaching or exceeding 35°C in more than one in ten realisations. For example, in 2060 and for the option where we commit to no CDR and slow Dec, the regions affected are Western Africa and the Arabian Peninsula. Whereas there are 11 regions affected by the no CDR and slow Dec option from 2100 onwards. It is possible to provide for each region the number of lost options at which its temperature reaches 35°C in more than one in ten realisations. This variable is represented in the following map (Figure 10).

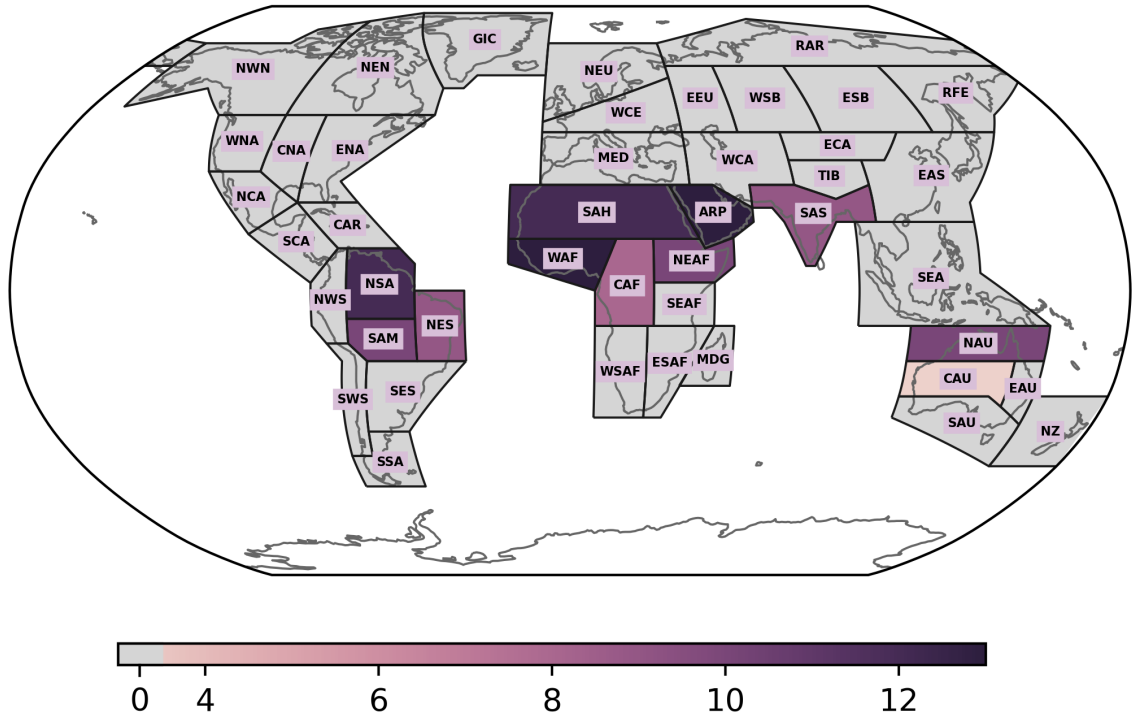


Figure 10: Number of lost options for each region in the first experiment.

This map allows the understanding of which regions are affected by the lost option metrics. There are spatial and temporal inequalities in the effect of lost options commitment. Of the 44 regions, 11 are affected: Northern South America (NSA), North-Eastern South America (NES), South American Monsoon (SAM), Sahara (SAH), Western Africa (WAF), Central Africa (CAF), North Eastern Africa (NEAF), Arabian Peninsula (ARP), South Asia (SAS), Northern Australia (NAU) and Central Australia (CAU). Options are being lost because of excessive warming of one or more of these regions. Many northern countries are never affected by excessive temperatures. For each of these regions, it is possible to identify the first year in which the 90th percentile exceeds 35°C . Within a given scenario and option, this year is not always the same from one region to another.

All thirteen lost options are due to the warming of at least two regions: ARP and WAF. In the worst-case scenario, the MAT in WAF reaches 35°C in 2260, while in the ARP this happens in 2269. If we commit ourselves in 2060 to slow Dec, the temperature of WAF will reach 35°C in 2613, while the ARP will reach this temperature in 2585.

Lost options commitment in 2070, 2080, 2090 and 2100 involve, in particular, NSA and the SAH. In the worst-case scenario, the MAT in NSA reaches 35°C in 2325, while in the SAH this happens in 2315. If we commit ourselves in 2070 to slow Dec and strong CDR, the temperature of NSA will reach 35°C in 2613, while the SAH will reach this temperature in 2447.

SAM, NEAF and NAU regions see their temperatures exceeding 35°C in ten lost options commitments. For the slow Dec and no CDR in 2100, the lost options commitment happens in 2457 for SAM, 2464 for NEAF and 2425 for NAU. The latest these regions are affected is for the slow Dec and no CDR option in 2070, with 35°C reached in 2997 (SAM), 3307 (NEAF) and 2770 (NAU).

In SAS and NES, only nine options through all tested scenarios are lost. SAS will not be affected if we commit to any option before 2080 or if we commit to medium or fast Dec options in 2080, 2090 or 2100. In the worst-case scenario, the MAT in SAS reaches 35°C in 2522. If we commit in 2080 to slow Dec and strong CDR, SAS reaches the limit in 2764. In the latter option, NES doesn't reach 35°C. But this will happen in 3453 if we commit in 2070 only to slow Dec (while in this scenario SAS is safe). In the worst-case scenario, the MAT in NES reaches 35°C in 2497.

CAF is affected by eight lost options: three in 2100, three in 2090 and two in 2080 (slow Dec with no CDR or weak CDR). In the worst-case scenario, the MAT in CAF reaches 35°C in 2509. If we commit in 2080 to slow Dec and weak CDR, this happens in 2631.

CAU is never affected unless we commit to a slow Dec and no CDR option in 2100, 2090 or 2080. In the worst-case scenario, its MAT reaches 35°C in 3042. For the lost option of 2080, its temperature reaches 35°C in 3448.

4.2 Sensitivity experiments

4.2.1 Sensitivity to temperature criteria

The second experiment is slightly different from the first one: instead of setting the climate target at 35°C, we ask ourselves what happens when we specify the limit of the operating space at a MAT of 30°C. This can be justified by the fact that while an MAT of 35°C is unbearable, it is also worth looking at the situation for conditions that are a little less extreme but still concerning. As awaited, the results are less optimistic. It also shows that the experiment is very sensitive to the criteria chosen. The window of opportunity is given at the following figure (Figure 11).

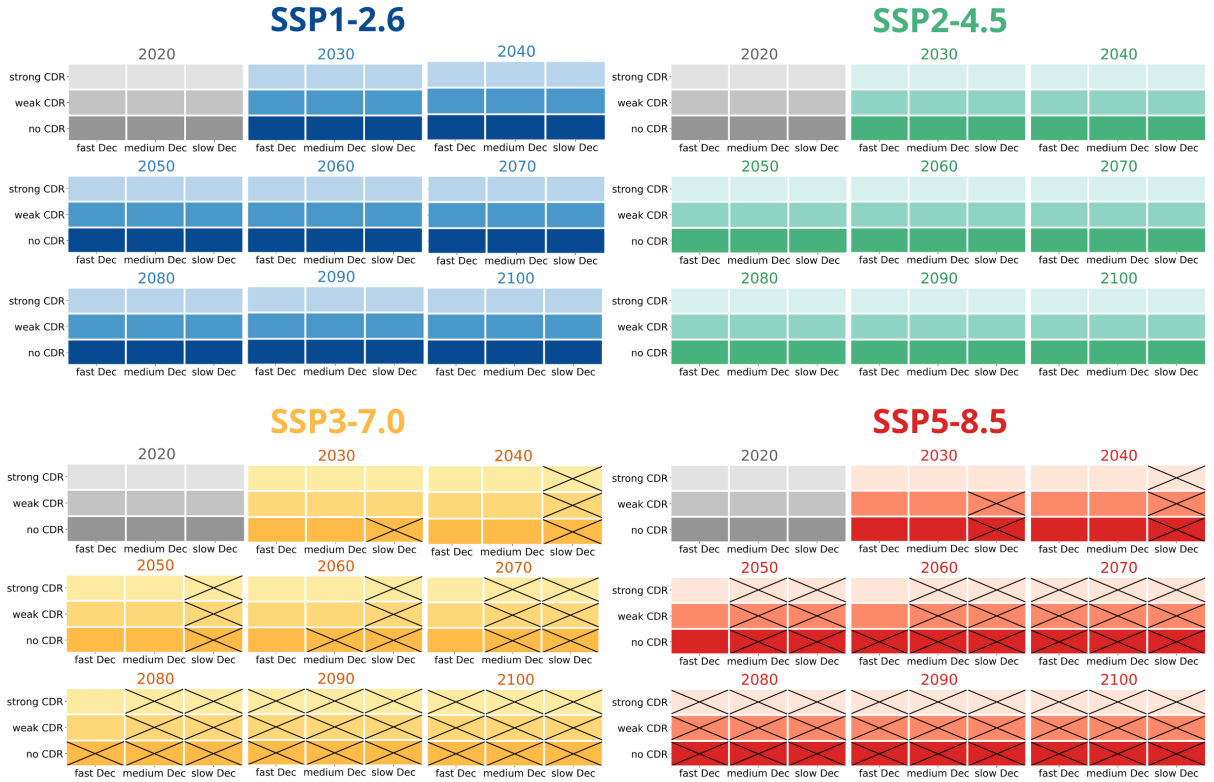


Figure 11: Window of opportunity of the four SSPs in the second experiment. Options that transgress the target are crossed out.

In this case, 96 options out of the 324 options are lost. SSP1-2.6 and SSP2-4.5 are still safe. Options are lost if our societies follow the SSP3-7.0 and SSP5-8.5 and a lot earlier than in the first experiment.

In the case of the SSP5-8.5, 54 options are lost. All commitment options envisaged from 2070 onwards are lost. In 2060, the only available options are those where we com-

mit to fast Dec and weak CDR or strong CDR options. In 2050, the only way to prevent a region of the world from reaching 30°C of MAT is to commit to a strong Dec. If we commit in 2040, fast Dec and medium Dec options are available. If we take action as early as 2030, it will be enough to commit to any other option than a slow Dec option with no CDR or with weak CDR.

In the case of the SSP3-7.0, 42 options are lost. All commitment options considered in 2090 and 2100 are lost. In 2080, the only available options are those where we commit to fast Dec and weak CDR or strong CDR options. The 2080 commitment year for the SSP3-7.0 is similar to the 2060 commitment year for the SSP5-8.5. The 2070 commitment year for the SSP3-7.0 is similar to the 2050 commitment year for the SSP5-8.5: only fast Dec options are available. If we commit in 2060, slow Dec options and medium Dec without CDR option are lost. The 2050 and 2040 commitment years for the SSP3-7.0 are similar to the 2040 commitment year for the SSP5-8.5: only slow Dec options are lost. In 2030, the slow Dec without CDR option is lost.

The same map as in the first experiment is produced for the 30°C target used here. The results are shown on Figure 12. The regions that already met the lost option in the first experiment have, predictably, a much higher number of lost options in this experiment. There are now 22 regions affected, i.e. half of all regions, or double the number of regions affected in the first experiment. North America, Europe, Russia, China and Japan are still never concerned. The 11 new regions at risk in this experiment are Northern Central America (NCA), Southern Central America (SCA), Caribbean (CAR), North-Western South America (NWS), South Eastern Africa (SEAF), West Southern Africa (WSAF), East Southern Africa (ESAF), Madagascar (MDG), West Central Asia (WCA), South East Asia (SEA) and Eastern Australia (EAU). If we set the unwanted state at 30°C instead of 35°C, almost whole Africa could potentially be affected by at least one lost option.

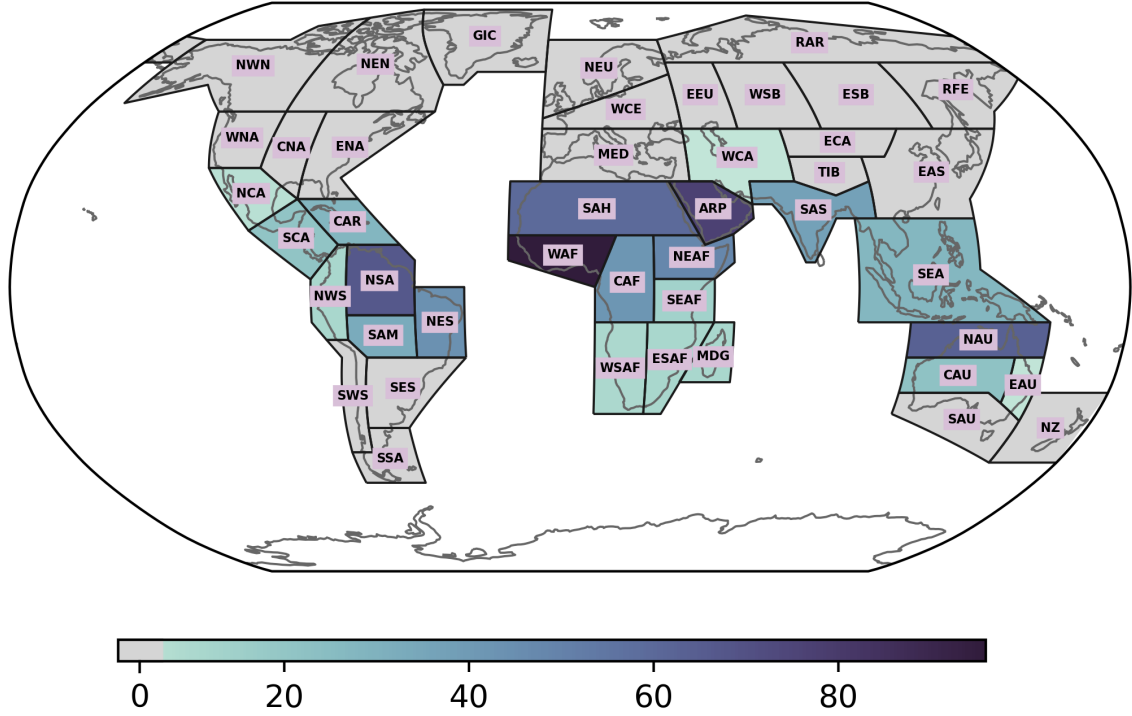


Figure 12: Number of lost options for each region when the temperature criteria is set at 30°C.

If we follow the SSP3-7.0, 14 regions of the 22 are affected by at least one lost option. The 11 regions that were affected by at least one lost option in the previous experiment are all affected by at least one lost option in the SSP3-7.0 scenario. The other three regions are SEA, the CAR and SCA. This means that the remaining eight regions are only affected by the lost options that occur in SSP5-8.5.

For each lost option in the previous grid (Figure 11), there is a risk that the MAT in WAF will exceed 30°C. WAF is the only region affected by lost options in 2030 (for both scenarios). While the ARP had the same number of lost options as WAF in the previous experiment, this is no longer the case here. With the 30°C rather than 35°C criterion, 77 options are lost for the ARP. The region with the fewest lost options is EAU with three lost options.

For each of these regions, it is possible to identify the first year in which the 90th percentile exceeds 30°C. Within a given scenario and option, this year is not always the same from one region to another. The years in which the safe operating space is crossed are around 2200. The minimum is 2087 for WAF in many lost options. The maximum is 3566 for WCA in the worst-case scenario.

4.2.2 Sensitivity to number of realisations

In the third experiment, we are following the same conditions as in the second experiment (unwanted state at 30°C) but we produce 100 realisations instead of 10 and we focus only on the window of opportunity for the SSP3-7.0 (Figure 13).

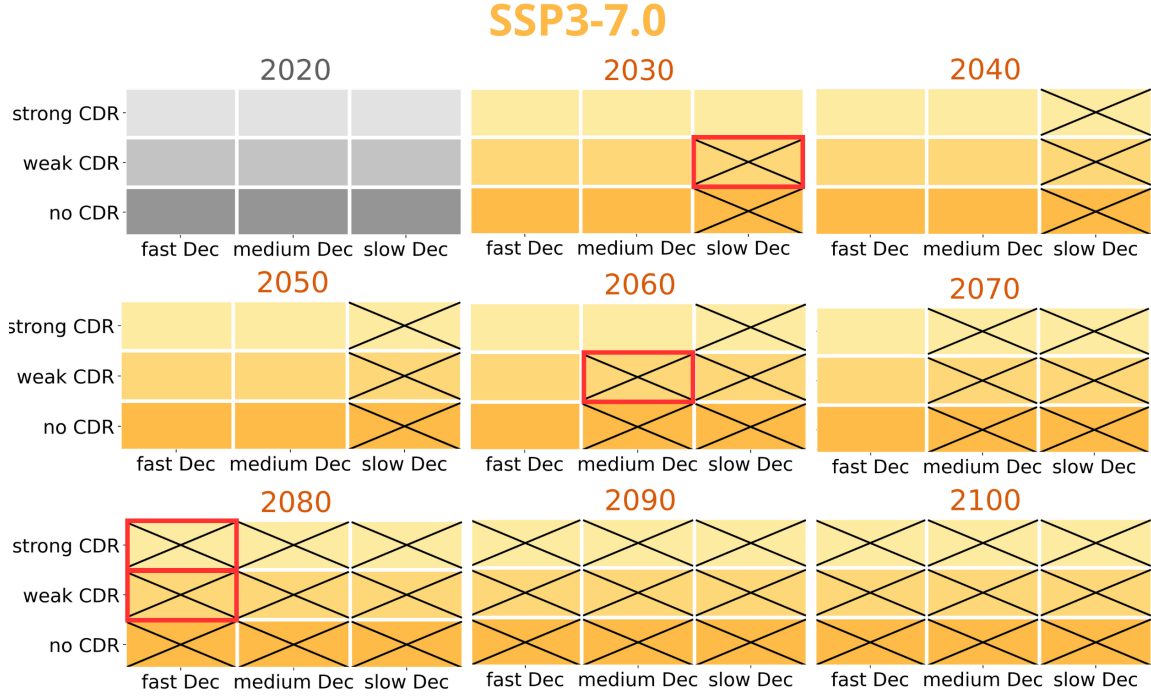


Figure 13: Window of opportunity of the SSP3-7.0 in the third experiment. Options that transgress the target are crossed out. Lost options in this experiment that were available in the second one are framed in red.

In this experiment, 46 options are lost instead of 42 in the previous experiment. The new lost options are the slow Dec and weak CDR in 2030, the medium Dec and weak CDR in 2060, the fast Dec and weak CDR in 2080 and the fast Dec and strong CDR in 2080. All 2080 options are lost, as are those for 2090 and 2100. In 2070, only the fast Dec options are still available. In 2060, it is also possible to commit to the medium Dec and strong CDR options. In 2040 and 2050, slow Dec options are lost. The options lost in 2030 are slow Dec without CDR or with weak CDR.

The number of regions affected is 14 and they are the same as those of SSP3-7.0 in the previous experiment. The other 30 regions do not have a single realisation where the temperature exceeds 30°C in the SSP3-7.0. All 14 regions have an increasing number of lost options in this experiment.

The four new lost options of WAF are those framed in red. Moreover, the WAF region is the only one concerned by these lost options. In general, when there is a lost option for the WAF region, the 100 realisations exceed 30°C . For the four new lost options this number varies from 14 to 47. The regions that have one more lost option in this experiment compared to the second one are SCA, CAR, NSA and CAF. The regions gaining two new lost options are NEAF, SAS and SEA. The regions gaining three new lost options are NES, SAM, SAH and CAU. The ARP has five new lost options. The NAU is the region with the most new lost options with six of them.

The number of realisations exceeding 30°C varies from one lost option to another. For the new lost options, this number ranges from 11 to 100. Some options had 9 realisations exceeding 30°C for some regions of Africa but, in line with the method, they were considered as available options.

4.2.3 Sensitivity to the stochastic process

The objective of the fourth experiment is to determine the influence of the stochastic probability on the results. In this experiment, we do not produce stochastic realisations: the model is deterministic. The smooth curve of the temperature anomaly is used without stochastic realisations and we focus only on the window of opportunity for the SSP3-7.0 (Figure 14). The unsafe criteria is set at 30°C .

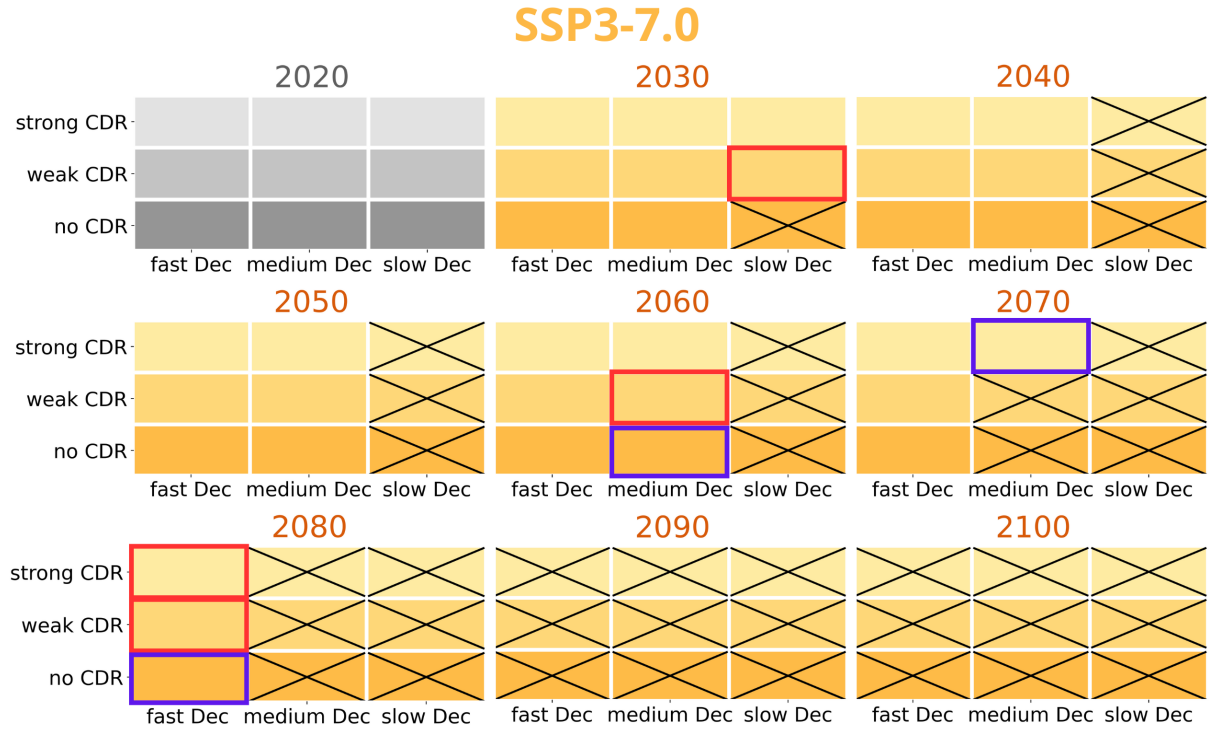


Figure 14: Window of opportunity of the SSP3-7.0 in the fourth experiment. Options that transgress the target are crossed out. Available options in this experiment that were lost in the second one are framed in blue. Lost options in the third experiment that were available in the second one are framed in red.

In this experiment, 39 options are lost instead of 42 in the second one and 46 in the third one. The three available options that were lost in the second experiment are the medium Dec and no CDR in 2060, the medium Dec and strong CDR in 2070 and the fast Dec and no CDR in 2080.

The same 14 regions remain affected. But the moment when the safe operating space is reached usually comes later. Some regions have one or two additional available options. This is the case for four regions: the SCA, the NSA, the SAH and the NEAF. WAF has four additional available options. Some regions have one or two additional lost options. This is the case for four regions: the SAM, the CAF, the ARP and the NAU. Some regions keep the same number of lost options and the same lost options. This is the case for five regions: the CAR, the NES, the SAS, the SEA and the CAU.

Chapter 5

Discussion

Several aspects of the four experiments can be analysed and discussed, such as the definition of scenarios and options, the choice of temperature criterion, the effect of the stochastic process or the number of realisations. The results are then briefly compared with the literature. The third section discusses the strengths and limitations inherent to the method. Finally, suggestions for improvement are given.

5.1 Results interpretation

5.1.1 Options and scenarios

Based on the different experiments it is possible to draw conclusions on the various options and scenarios. For each of the following comments, the effect is more visible for experiments with 30°C as the temperature criterion.

First we see that the longer we wait to make a commitment, the more future generations lose options. Each decade has fewer and fewer available options, until there are none left for the last few decades (for the SSP5-8.5 with 35°C and for the SSP3-7.0 and SSP5-8.5 with 30°C). In other words, the window of opportunity for future generations is smaller than the current window of opportunity. The capacity of future generations to meet their needs, i.e. to remain in the safe operating space defined here by temperature, is lower than the current capacity. We note that this is in contradiction with sustainable development.

Then we see that for the 30°C experiment, all the options with no CDR are lost from 2080 for the SSP3-7.0 and from 2060 for the SSP5-8.5. The longer we wait before drastic reductions in emissions, the more we commit future generations to using technologies that do not exist, yet. The weak and strong CDR rates considered in this work do not reflect the performance of current technologies. Currently available technologies are at best consistent with the needs to be met to follow SSP1-2.6 (Martínez Montero et al., 2024). Remember that these two rates are -1 GtC/yr and -2 GtC/yr . In comparison, the oceans have a mean uptake of $-2.6 \pm 0.4 \text{ GtC/yr}$ for the period from 2013 to 2022 while the lands

have a mean uptake of $-2.1 \pm 1.1 \text{ GtC/yr}$ for the same period (Friedlingstein et al., 2023).

For the first set of experiments with 35°C as the temperature criterion, the result looks rather optimistic. Indeed, only 13 of the 324 options considered were lost. The question here is to what extent this result is really reassuring. First of all, it is important to understand what a MAT of 35°C implies. This will be addressed in the next section. Then we need to take into account the probability that the scenario will come true and be maintained. It was not the aim of this work to establish the plausibility of each scenario and option, and it would be nice to establish it in future work. The rest of the discussion should therefore be treated with caution.

It is reasonably probable that we will follow a scenario that present a lost option. In any case, those options seem more likely than those where we act as early as 2020 or 2030, following either SSP1-2.6 or SSP2-4.5. These two SSPs make it possible to achieve the objectives and carbon neutrality in 2050, but assume that emissions will fall at the rate imposed by the global pandemic in 2020, every year for the next six or seven decades (IPCC, 2023). If this intuition is correct, the window of opportunity is not as wide as this study shows. But on the other hand, following SSP5-8.5 requires discovery of new oil deposits or better extraction rates technologies (IPCC, 2023).

There is also uncertainty about the ability to follow an option and maintain it. In the case of CDR, as we have said, the rates envisaged are not yet within our reach and may never be. All CDR options before 2040, for example, may not be very plausible. It could be years before we know which methods work in the real world and not in a laboratory, and whether they harm or benefit the environment (Ho, 2023). If it is possible to achieve these CDR rates, we must also assume that the market will produce the technology on its own, according to its own logic and in time. Even if these technologies do emerge, it is uncertain whether they can be maintained in a changing climate, possibly with unstable political regimes (which could happen with rising temperatures). What would happen if some decision-makers estimate that the budget allocated to research and development of these technologies is too high? Especially for options where the CDR is only accompanied by a slow Dec and that it therefore has a greater role in the reduction of carbon in the atmosphere. Another issue is the uncertainty regarding the compatibility of CDR and fast or medium options. In some cases, improving a technology that increases the efficiency with which a resource is used can increase the consumption of that resource. This paradox is known as the rebound effect or the Jevons paradox (Alcott, 2005). In other words, if we manage to develop such CDR technologies, how can we be sure that

they won't be accompanied by an increase in consumption? And so, is it plausible to have both fast Dec and strong CDR? Finally, the plausibility of a change in behaviour leading to a fast or medium Dec can also be discussed. It's unlikely that such a change will happen any time soon. Just as it is not as likely to happen in the various SSPs.

In the end, perhaps the most plausible scenario is to do nothing which means following SSP5-8.5 (business as usual). But according to the decision theory, the result of a rational analysis is as follows: in the case of uncertain knowledge, the best option is to do nothing (Giere et al., 2006). So we need to see to what extent work like this one defuses the uncertainty associated with decisions. The caution of the results of the first experiment is consequently relative. And the results, particularly of the second experiment, can be read in the light of the nuances introduced above.

With the 30°C criterion, the options where we commit to slow Dec leave the safe operating space from the moment they are taken in 2040. What's more, if we want to stay within the safe operating space of 30°C and we don't think we can take on medium or high rates of Dec, we should have committed to these options in 2020. If we don't think we can commit to anything other than slow Dec, we will have to develop technologies that allow us to commit to weak or strong CDR and commit in 2030 to following this option. If, on the other hand, we do not want to use CDR technologies, we will have to commit to medium Dec before 2050 or fast Dec before 2060 if we follow SSP5-8.5. If we follow SSP3-7.0, we will have to commit to medium Dec before 2060 or fast Dec before 2080.

If we take a path that leads us to a lost option, there are also uncertainties. There is a significant time lag between the moment when we take a decision that condemns us and the moment when other generations are affected. There is uncertainty about how our behaviour will unfold between now and then. We could manage to adapt to these temperatures, or we could manage to move entire populations without worry. It is also possible to discuss the plausibility of this course of action.

5.1.2 Temperature

The second experiment shows that changing the temperature criterion can affect the number of lost options. Setting the target at 30°C rather than 35°C means losing 83 available options. The key point is the difference between a MAT of 30°C and 35°C. As previously announced, it is important to understand what a MAT of 35°C implies. Firstly, it means daytime temperatures well above than 35°C. In 1999, the average annual

impacted by rising temperatures, the same is true for the rest of the world. Indeed, some of these regions have large cultivated areas. This is true of Nigeria with 70.8 million hectares of agriculture land area, India with 170 million hectares of croplands and Brazil with 278 million hectares of agricultural lands (FAO, 2022). As explained in the literature review, high temperatures can have an effect on crop growth or on the laboriousness of cultivation work. Equatorial forests are also affected, particularly the Amazon rainforest. Ecosystems have the capacity to adapt, but there is a limit to how far it can go.

The safe nature of certain regions is also up for discussion. In many options, the Sahara and Australia are classified as "safe" in our analysis, even though these regions are already not part of our liveable area. Indeed, temperature is not the only determinant of the human climate niche. Other factors include proximity to the coast and annual precipitation (Small and Cohen, 2004). We have to focus on the tension between the expected human inhabited area and the future locations of the climatic conditions that have enabled us to develop. This conclusion is supported by other studies (Xu et al., 2020; Lenton et al., 2023).

5.1.3 Number of realisation and stochastic vs deterministic

The third and fourth experiments provide further information on the usefulness of the stochastic process. First of all, we notice with the third experiment that generating more realisations results in more lost options. First, because for some regions and options, the number of realisations goes from 0 out of 10 to 11,12,13, etc out of 100. Second, because the two methods differ slightly. Let's remember that when we take as a criterion that one in 10 realisations exceeds 30°C, we impose that as soon as the 90th percentile of a year exceeds 30°C, the option is lost. When we say that 10 out of 100 realisations must exceed 30°C, we're not looking at year after year, but at the whole period. The 90th percentile estimated for a given year is not used. In the first experiment, a region may have its ten realisations exceeding 30°C, but for different years, with the potential effect that the 90th percentile of a year will not exceed 30°C. In this case, there is no lost option, even though all 10 realisations exceed 30°C. This is not a problem with the other method, since it was decided to proceed differently. An example is shown in the figure below (Figure 16). We are in the SAM region for the SSP3-7.0 scenario with a slow Dec and medium CDR option taken in 2080. Each of the 10 realisations exceeds 30°C at some point (sometimes several times). However, every year, the 90th percentile is lower than 30°C. So the option is never lost.

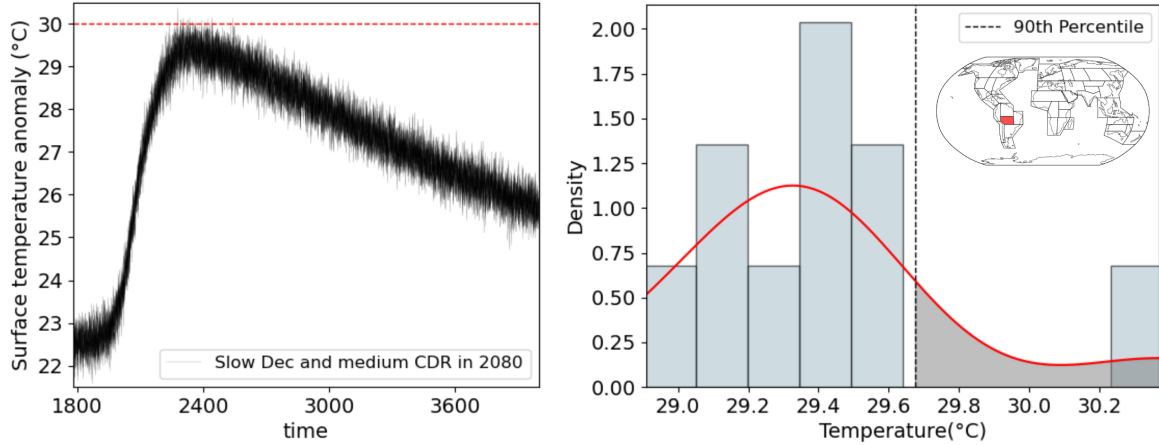


Figure 16: Illustration of the problem arising from the 90th percentile method. On the left, the temperature distribution of the 10 realisations for the SAM region. On the right, the probability density (in red) in 2278 for the same region. Each of the 10 realisations exceeds 30°C at some point. However, every year, the 90th percentile is lower than 30°C .

Setting the criterion at 10% is subjective; it all depends on how much risk we are willing to take. Choosing the percentage at which you decide that the option is lost is a matter of choosing whether you prefer to detect a lost option that will not arrive or to have an available option that is in fact lost. In the first case, a higher percentage is chosen. In the second case, a lower percentage is chosen. This said, this choice does not appear to crucially affect the main message. In many cases, the number of realisations above 30°C is much higher than 10%, even reaching 100%.

In the fourth experiment, we estimate the effect of a deterministic rather than a stochastic trajectory. Choosing a deterministic trajectory results in the loss of many nuances, often leaving lost options undetected in some regions. However, we noted four regions that had more lost options with a deterministic trajectory than with ten stochastic trajectories. This can also be explained by the 90th percentile issue. With the deterministic trajectory, as soon as 30°C is exceeded, the option is lost.

5.2 Comparing results with the literature

As the framework of this study is highly inspired by Martínez Montero et al., 2024, we can briefly compare the different results. The Martínez-Montero analyses which options lead to a 3 metre rise in sea levels. For the 4 scenarios, the first study shows more lost options than here. If we compare our results at 30°C, there are one or two more options per assessment year in the previous study. Unlike here, the sea level study had lost options even for the two most optimistic SSPs. One thing we can learn from the comparison is that this study does not condemn any more options than the one on sea levels, except for one. This is the slow Dec and strong CDR option in 2080 for the SSP3-7.0 when generating 100 realisations.

A first explanation can be given by the difference in criteria. In the Martínez-Montero analysis, the trajectories are deterministic. Here, however, a probability is established. The trajectories are stochastic.

The second difference is inertia. In this work, it is the inertia of the carbon cycle that drives the temperature. In the other study, it is the inertia of the thermal response that drives sea levels. In our case, the time lag between our decision and the mitigation reflects the slow absorption and release of carbon by natural reservoirs such as oceans and forests. We note that when we take a decision to reduce carbon in the atmosphere, the land cools more quickly than the oceans because of its lower inertia.

5.3 Strengths and limitations

The methods and results met the expectations. One of the great strengths of this work is the method. It is easy to understand and simple to implement and reproduce. It is also modular and can be adapted to expertise criteria other than those used here.

This last point is also one of its weaknesses. The definition of the unwanted state is arbitrary. It can be difficult to justify when an unethical boundary is crossed. In the case of this study, it is already difficult to say whether 30°C or 35°C is the limit that should not be crossed. The same applies to the choice of the probability of the event occurring (as discussed above). Even if we recall that in several cases, the regions have a 100% chance of exceeding the criterion established.

Another limitation is that we have not attempted to quantify the physical uncertainties. There are uncertainties about the overall scenario, uncertainties about climate

sensitivity and other physical uncertainties. For example, we make long-term projections. We cannot be certain of the reliability of the scenario in such a distant future. To sum up, our knowledge of the present state, our representation of nature and our knowledge on future boundary conditions are imperfect and biased. Incidentally, the study is not focused on storyline analyses; we did not focus specifically on the worst-case scenario. The representation of physical processes was not tailored for this purpose. Yet, we still considered unfavourable scenarios through the definition of the lost option criterion.

The inherent limitation of the method is the number of scenarios considered. As explained at the start of this discussion, not all scenarios have the same probability of occurring. But the more options we consider, the more unlikely the lost options seem. When in fact, this is not necessarily the case if lost options are more likely than other options.

5.3.1 Modifiable Areal Unit Problem

A modifiable areal unit problem (MAUP) refers to "the cartographic representation of data whose attributes are significantly influenced by the spatial scale used" (Buzzelli, 2020). A MAUP is obvious here, since it is possible that another classification with a different division would give different results. It might, for example, be possible to manipulate the region boundaries so that a hotspot is (or is not) in a region when calculating the average temperature, which would not lead to the same conclusion. However, the region boundaries are not chosen for this purpose; they are chosen for their universality, which allows comparison. Nevertheless, the risk of a possible bias must be kept in mind.

5.3.2 Scale effect

One sub-problem of the MAUP is known as the scale effect. A certain resolution is used and then an average is calculated to obtain a mean temperature on the scale of the region. It is on this last result that we draw a conclusion as to whether the scenario is safe or unsafe. Unfortunately, this method can lead to an ecological fallacy. It can have the effect of unifying the temperatures of an entire region and hiding more local disparities. There is also a risk of drawing an invalid conclusion. We could face a situation where the temperature of a region exceeds 35°C on average, but with the uninhabited half at 40°C and the inhabited half at 30°C. In such a case, we would be drawing an invalid conclusion because the inhabited part of the region doesn't exceed the threshold we've set. Conversely, there may be an inhabited area where the temperature will rise considerably, but within an uninhabited region with colder temperatures. In that case, we would have a reassuring scenario that is in fact misleading. This is a limit of the method that is

caused by the need for simplification. We make the simplifying assumption that a region above 35°C is, in all cases, uncertain as regards its future.

5.4 Suggestions for improvement

An improvement would be to use the WBT instead of the temperature. When accounting for the psychological function, the WBT is a better predictor of habitability. In fact, this is what is used in Lenton et al., 2023. The WBT is the lowest temperature that can be reached under current ambient conditions by the evaporation of water only. Humans use perspiration to cool their bodies, which is no longer possible when the WBT exceeds 35°C. With that being said, in a humid environment, these two measurements are very close. And the results of this study show that humid environments are the most affected areas.

Since a MAT of 30-35°C is likely too extreme, we could study temperatures during the warm season or extreme events. To this end, other versions of MESMER can be used, such as MESMER-M (Nath et al., 2022), which can give temperatures by month and focus on hot months, or MESMER-X (Quilcaille et al., 2022), which gives climate extremes. With the first model, we would have the same output except that we would have 12 temperatures instead of one per year. With the second model, we would use the annual maximum of the daily maximum temperature. This would make it possible to quantify the probability of an extreme event occurring in one year compared with another.

Another improvement would be to use several models. Only SURFER is used to model the global temperature response resulting from our emissions commitments. This is advantageous because this model is easy to use and quick to run. But it is also useful to use several models to reduce global uncertainty, capture the complexity of the Earth system as a whole, enhance confidence in the results and identify which parameters have the greatest influence on the results. That said, SURFER is modular and can be calibrated to reproduce other models (with the MAT as an output).

One contribution of this study is that it is possible to see the regional effects of global decision-making. One improvement would be to be able to assess decisions taken at regional rather than global level. Here, the options are lost on the basis of temperatures, but we can also decide to evaluate the available options for each region on the basis of their regional operating space. Some regions may not be able to follow some options if, for example, their emissions are already very low. Such an analysis would make it possible to see which regions have the capacity to commit (for the rest of the world) to following one

of the available options. Perhaps the regions that can commit to the available options in the analysis are those that are not affected by a lost option.

These results could be coupled with population distribution prediction models (which could take migration into account). This would give an idea of the number of people potentially affected. However, the uncertainties are high and these models are often very deterministic (Gemenne and Cavicchioli, 2010). What's more, the population would have to be projected well beyond 2100.

If the aim is to define the entire safe operating space, other aspects of the boundaries that must not be transgressed need to be addressed. These could be tipping points or the social foundation of the safe and just operating space as defined by Kate Raworth (Raworth, 2012). To begin with, it is possible to associate temperatures with other undesirable effects. For example, it is possible to set the unwanted state on the temperature of the poles and find out which commitments lead to irreversible melting. If it is a too rapid change in temperature that we want to avoid, it is also an improvement that could be made using the method applied here. It is further possible to translate the temperature increase into unwanted state. For example, if we have an estimate of the temperature that would trigger civil war in some countries. If we want to know which commitments are leading to the disappearance of a species that is important to us, or an increase in the ecological niche of a dangerous species (mosquito, tick), or a weakening of food security, the method can be used.

Chapter 6

Conclusion

As we have seen, the safe operating space was conceptualised in 2009 by Johan Rockström. Since then, this concept has found many applications. This is also the aim of this work. We argue that the safe operating space is characterised not only by the state of the system but also by the controls that allow us to stay in the safe space. This is an important issue because it allows us to know the limits of our actions without having to experiment them. In this work, the aim was to explore the different commitments that our societies can make collectively and to see in which cases we reach a state that we do not consider ethical.

We have defined nine commitment options based on decarbonisation and carbon dioxide removal. Every ten years between 2020 and 2100, we can commit to one of these nine options. This framework is applied to each of the following SSPs: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. Our study uses as climate target avoiding a MAT of 35°C in one region of the world within a time horizon of 2000 years and a set of 9 long-term scenarios as possible options. With the SURFER model, each of the 324 global warming trajectories is generated. With the MESMER model, noise is added to each of these trajectories to give ten stochastic realisations instead of one deterministic one. After several manipulations, a global temperature map is obtained for each year and each realisation. It is this last step that enables us to determine whether a region of the world has a MAT that exceeds 35°C in more than one in ten cases. We use the 90th percentile to determine whether this is the case. We then carry out a sensitivity analysis. We analyse the effects of changing the temperature criterion, increasing the number of realisations generated and using a deterministic trajectory rather than ten stochastic ones.

The aim of the work was multiple. We asked: what does the safe operating space look like when we explore different degrees of political commitments? What is the effect of the choice of criterion defining the unwanted state? What is the effect of changing the number of realisations? What is the effect of adding the stochastic process? How does the unwanted state apply spatially? As we have seen, the longer we wait to make a commitment, the more future generations lose options. The more we do nothing, the more we commit future generations to using technologies that do not yet exist. The

change in unwanted state, from 35°C to 30°C, has a major impact on the results: it considerably increases the number of lost options. By increasing the number of realisations, we decided to change the method. This resulted in the addition of four lost options for the SSP3-7.0. Using one deterministic trajectory rather than ten stochastic trajectories transforms three lost options into available options. The regions of the world are unequally affected by political decisions. Equatorial regions are more often affected by lost options than other regions of the world. The regions that exceed the ethical target the most are Western Africa, the Arabian Peninsula, India and the Amazon rainforest.

A number of limitations have been identified. The various options defined are not directly comparable, since they do not have the same probability of occurring. Furthermore, the aim of this work was not to establish these probabilities. The temperature criterion used in the analysis is probably responsible for the lack of lost options. The temperature of 35°C describes a very extreme world. Using the 90th percentile can lead to an overestimation of the number of available options. We have not attempted to quantify the physical errors and uncertainties. While this limitation can be resolved, it is not the case of the MAUP, which is inherent in the method.

This study produced some interesting results. The concepts of lost options commitment and safe operating space fit together successfully to provide a deeper understanding of the different options available to us. There are still many limitations, most of which can be improved. Using a probabilistic assessment of future regional temperatures based on the notion of lost options commitment is something new. The method used could be transposed to other areas of expertise without too much difficulty. This could prove very useful in understanding the climate problems we face and making the right decisions.

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