Abrupt Climate Changes and Tipping Points: Epistemic and Methodological Issues

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1 Introduction

Large-scale and discontinuous rapid transitions in the climate and Earth systems constitute one of the most concerning, yet in many ways one of the least understood aspects of climate change. On the one hand, because of their potential huge impacts on human and ecological systems, it is argued that climate tipping points and their interactions (potentially leading to cascading effects) help "to define that we are in a climate emergency" (Lenton et al. 2019, 592). On the other hand, it is largely acknowledged that making quantitative (e.g. probabilistic) statements about abrupt climate changes and tipping points is extremely challenging (NcNeall et al. 2011). Some form of tension thus emerges from these two sides of abrupt climate changes and underlies the development of the very notion of climate tipping point (for a review of this development, see Russill 2015). This tension finds its roots in the many epistemic and methodological issues that arise in the context of abrupt climate changes and tipping points. This contribution aims to provide an overview of these issues in a philosophy of science perspective; the expectation is that such a conceptual perspective can help to improve our understanding of the specific challenges related to abrupt climate changes and tipping points.

The topic is actually getting increasing prominence in climate science (as well as in other disciplines), as manifested for instance by the increasing number of publications related to abrupt climate changes and tipping points (on this latter notion, see some bibliometric evidence in Milkoreit et al. 2018) as well as recently by the dedicated chapter in the Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC 2019, ch. 6) of the Intergovernmental Panel on Climate Change (IPCC).[1] Depending on the context, the very concepts of abrupt change and tipping point actually point to a variety of different physical and mathematical notions, such as feedback and non-linearity, threshold and phase or critical transition, multistability, hysteresis and bifurcation.[2]

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[1] There is also a proposal prepared by some countries and parts of the climate science community for an IPCC Special Report devoted to the issue of tipping points and impacts to be prepared during the seventh assessment cycle (AR7) of the IPCC (T. Stocker, private communication, June 2021)

[2] See for instance the discussion based on a large bibliographic review across domains in Milkoreit et al. (2018). On this basis, they suggest the following general definition: "tipping points *in general* can be defined as the point or threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by

However, there is up to now very little discussion in philosophy of climate science of the conceptual, epistemic and methodological issues raised by the many different aspects of abrupt changes and tipping points in the climate and Earth systems, despite their relevance not only from a philosophy of science standpoint but also in view of the climate challenge more generally.[3] This contribution is less an exhaustive overview of these issues than an invitation to philosophers of science (as well as to climate and Earth system scientists)[4] to turn their attention to them.

We discuss the standard definitions of abrupt climate change and of tipping point for the climate and Earth systems in sections 2 and 4. In section 3, we very briefly present a few basic elements of dynamical system theory, which mathematically encode the idea of a qualitative change that is at the heart of the notions of abrupt climate change and tipping point. We then review three families of epistemic and methodological issues related to the scientific relevance of the concept of tipping point (section 5), to tipping points as a tool in climate change communication (section 6) and to the social science perspective on tipping points (section 7). We conclude in section 8.

2 Defining abrupt climate changes

From a conceptual point of view, and in order to avoid any confusions, it is crucial to define precisely the notions we are interested in; conceptual clarity is indeed especially important in a scientific context with such societal relevance as climate science.[5] In this section, we highlight the relevance of such conceptual clarity when defining abrupt climate changes.

Let us consider the IPCC definition of abrupt climate change. In the Working Group I (which is concerned with "the physical science of climate change") contribution to the Fifth Assessment Report of the IPCC (AR5), we find the following definition (IPCC 2013, 1114):[6]

(ACC-1) We define *abrupt climate change* as a large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems.

This definition explicitly takes impact considerations—in particular, on human systems—and related relevant timescales ("a few decades") into account. Another standard definition—to be found for instance in the report of the Committee on Abrupt Climate Change formed by the US National Research Council—rather puts the focus on the response to an external forcing as well as to some threshold behaviour ((NRC 2002, 14)):

(ACC-2) Technically, an abrupt climate change occurs 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.

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system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible" (Milkoreit et al. 2018, 9)—we will of course return to various aspects captured in this definition in the subsequent sections.

[3] Unsurprisingly, abrupt climate change has been a bit more discussed in the climate ethics literature (see Gardiner 2011, ch. 6 for a prominent example). One of the goals of this contribution is to show that it also raises fundamental philosophy of science issues—some of which actually being not completely unrelated to practical philosophy and social science questions, as we will see.

[4] For the climate and Earth system scientists, this contribution can be seen as an invitation to interdisciplinary dialogue.

[5] In the philosophy of climate science literature, the need of conceptual clarity has been recently stressed in particular with respect to the central notions of climate state, climate change and climate sensitivity, among others (see Werndl 2016 and Katzav and Parker 2018).

[6] See also the recent IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), IPCC (2019, 594).

Since the two definitions (ACC-1) and (ACC-2) emphasize different aspects related to abrupt climate changes, they may well lead to different conclusions as to whether a given climate dynamics involves an abrupt change or not. For instance, certain shifts induced by "natural low-frequency climate variability" may be considered as abrupt following (ACC-1), but not necessarily so according to (ACC-2), since the considered change may not be due to any external forcing (Bathiany et al. 2016, 2-3); in other words, (ACC-2) may not allow for abrupt changes that are due to what is sometimes called 'internal variability', that is, without external forcings. In this sense, the definition (ACC-2) seems to require an internal/external distinction, which relies on how the climate system and its boundaries are defined—and such definition itself asks for careful attention (Katzav and Parker 2018, §2 & §4). Relatedly, and to complicate the matter a bit, one should take into account the fact that external forcings can influence internal variability—so that, "the contributions of forcing and variability cannot be clearly separated" (Bathiany et al. 2016, 3); this may lead to the ambiguity that what seems at first sight to be the consequence of internal variability can sometimes also be understood as the result of the influence of external forcings on internal variability.

In any case, it is important to note that both standard definitions (ACC-1) and (ACC-2) involve certain subjective components, e.g. about relevant timescales and what is considered as 'substantial disruptions' (ACC-1) or about what is considered as internal (external) to the climate system. In order to avoid any confusion, these subjective aspects and the ambiguities in defining abrupt climate change call for transparency about the definitions used. In particular, these subjective components may convey non-epistemic (e.g. social, ethical) values; transparency then involves these latter to be clearly identified (to the extent that is it is possible) and communicated along with the definitions used—and allowing for public debate.[7]

More generally, the notion of abrupt climate change as encoded in both definitions (ACC-1) and (ACC-2) seems to fundamentally involve the idea of a qualitative change in (the evolution of) the climate system—possibly triggered by some small perturbations, such as a small change in external forcing (ACC-2). This motivates a more mathematical perspective on abrupt climate changes, which we consider in the next section.

3 The dynamical systems theory perspective: bifurcations

The mathematical framework for studying the qualitative behaviour of physical systems such as the climate system is dynamical systems theory. In particular, this latter allows the study of the geometrical and topological properties of the set of all trajectories (orbits) of a dynamical system over time in state space (this set is called the phase portrait of the dynamical system). This is an extraordinarily rich and complex mathematical field and the purpose here is only to provide an intuition of the notion of bifurcation, which is the central tool for characterizing qualitative changes in dynamical systems, without entering into too many technical details. To this aim, we now introduce a few basic notions (we closely follow Kuznetsov 1998, ch. 1 & 2).[8]

In general terms, a dynamical system is characterized by the set of its possible states (called state space) and by a law of time evolution for these states.

(DS) A dynamical system is a triple $\{T, X, \varphi^t\}$, where T is a time set, X is a state space, and $\varphi^t : X \to X$ is a family of evolution operators parametrized by $t \in T$, such that φ^0 is the identity map and satisfying $\varphi^{t+s} = \varphi^t \circ \varphi^s$.

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[7] In many ways, the issue here echoes the recent discussion about non-epistemic values in climate modelling (see e.g. Winsberg 2012, Parker 2014 and Intemann 2015); see also the discussion in section 6

[8] See Scheffer (2009, Part I) for a non-technical introduction to key concepts of dynamical systems theory.

Depending on the context, either continuous-time dynamical systems ($T = \mathbb{R}$) or discrete-time dynamical systems ($T = \mathbb{Z}$) can be considered. In the continuous-time case, the time evolution is often characterized by a set of autonomous (time-invariant) ordinary differential equations, $\dot{x} = f(x)$, with $X = \mathbb{R}^n$ and (smooth) $f : \mathbb{R}^n \to \mathbb{R}^n$.

Since our aim is to study qualitative changes in the behaviour of dynamical systems—and of the climate system in particular—we need a way to compare dynamical systems, that is, to specify when they are or fail to be qualitatively equivalent: the relevant equivalence relation is topological here.

(EQU) A dynamical system $\{T, \mathbb{R}^n, \varphi^t\}$ is called topologically equivalent to a dynamical system $\{T, \mathbb{R}^n, \psi^t\}$ if there is a homeomorphism $h : \mathbb{R}^n \to \mathbb{R}^n$ mapping orbits of the first system onto orbits of the second systems, while preserving the time orientation.

A homeomorphism is a continuous invertible map such that its inverse is also continuous. If two dynamical systems are topologically equivalent, then their phase portrait can be continuously transformed into each other (since they are homeomorphic), which means that they have the same topological properties, such as the same number of invariant sets (equilibria / fixed points / attractors)[9], with the same (e.g. stability) features—hence qualitatively similar dynamical properties. Conversely, topological inequivalent dynamical systems may have a different number of invariant sets with different features, characterizing different dynamical properties. The notion of bifurcation precisely aims to capture these qualitative changes appearing as the parameters vary in parametrized dynamical systems (e.g. of the form $\dot{x} = f(x, \alpha)$, with $x \in \mathbb{R}^n$ and $\alpha \in \mathbb{R}^m$).

(BIF) The appearance of a topologically inequivalent phase portait under variation of parameters is called a bifurcation.

The value of a parameter at which the dynamical system undergoes a qualitative change in the here precisely defined topological sense is called bifurcation value or critical value. The qualitative behaviour of a dynamical system can be studied with the help of a bifurcation diagram, which, in rough terms, is the partition of the parameter space into regions with topologically equivalent phase portraits; the transitions between such regions then encode bifurcations. One of the main aims of bifurcation theory is the study and the classification of the various types of bifurcation in dynamical systems (there actually is an important variety of different types of bifurcations, such as for instance the saddle-node bifurcation, the Andronov-Hopf bifurcation, ...). In the climate context, a broad classification of (co-dimension 1) bifurcations[10] into three types, safe, explosive and dangerous, is often considered (Thompson and Sieber 2011).

Bifurcation theory encodes in precise mathematical terms central features associated with abrupt climate changes and climate tipping points, such as the existence of and the transition between multiple stable states or attractors, possibly involving some lack of reversibility (or some limited reversibility or hysteresis). In particular, bifurcation theory provides a precise topological

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[9] An attractor can be defined (Strogatz 1994, 324) as "a closed set A with the following properties:

1. A is an *invariant set*: any trajectory $x(t)$ that starts in A stays in A for all time.
2. *A attracts an open set of initial conditions*: there is an open set U containing A such that if $x(0) \in U$, then the distance from $x(t)$ to A tends to zero as $t \to \infty$. This means that A attracts all trajectories that starts sufficiently close to it. The largest such U is called the *basin of attraction* of A.
3. A is *minimal*: there is no proper subset of A that satisfies conditions 1 and 2."

[10] Co-dimension 1 bifurcations are bifurcations that can be associated with a single control parameter.

meaning to the notion of qualitative change, possibly triggered by some small change in parameter value. We do not intend to do justice to the fruitfulness of the interactions between this mathematical perspective and climate (and Earth system) science—that would go much beyond the scope of this contribution. But it is important to highlight that most results in bifurcation theory concern low-dimensional cases with very few parameters and so strictly speaking do not directly apply to the very high-dimensional climate (modelling) context with its huge number of parameters.

However, even in the high-dimensional cases, the behaviour of the system under consideration can be dominated by only a few positive feedbacks, so that bifurcations can be studied using low-dimensional techniques to some extent (this low-dimensional perspective has limitations though, see Bathiany et al. 2016). Furthermore, abrupt climate changes can be studied in climate models with the help of specific numerical methods exploiting bifurcation theory, called numerical bifurcation analysis; for instance, bifurcation diagrams can thus be produced for climate and Earth systems expected to undergo abrupt changes, such as in the case of the Atlantic meridional overturning circulation (AMOC) and marine ice sheets (see Dijkstra 2019 as well as references therein).

The notion of critical value or bifurcation value encodes in particular a threshold behaviour in abrupt climate changes, which is explicitly highlighted in definition (ACC-2). This threshold behaviour is at the heart of the concept of tipping point, which has gained increasing prominence in climate science (and beyond, see Milkoreit et al. 2018).

4 Defining tipping points in the climate and Earth systems

The concept of tipping point in the climate context is closely related to the notion of abrupt climate change, but it is however clearly distinct. In this section, we discuss distinctive features of the standard approach to climate (and Earth system) tipping points.

An important definition of tipping point in the climate context can be found in Lenton et al. (2008), to which most of the papers involving tipping points in the climate context refer.[11] A distinction is made between tipping element and tipping point, which are defined as follows (Lenton et al. 2008, 1786):

(TE) A tipping element Σ is a large scale (at least subcontinental) sub-system of the Earth system that is associated with a region or a collection of regions of the globe and such that the parameters controlling Σ can be combined into a single control ρ with a critical value ρ_c at which a small parameter variation $\delta\rho > 0$ leads to a qualitative change $\hat{F}$ in a crucial system feature F, after some observation time $T > 0$, measured with respect to a reference feature at the critical value, i.e.,

$$|F(\rho \geq \rho_c + \delta\rho | T) - F(\rho_c | T)| \geq \hat{F} > 0.$$

The critical point—in the control parameter (ρ_c) or the system feature ($F(\rho_c)$)—is then called a tipping point for Σ.

In the context of climate change, the subset of policy-relevant tipping elements is of particular interest (Lenton et al. 2008, 1787):

(PRTE) A policy relevant tipping element is a tipping element Σ satisfying the following conditions:

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[11] For a historical perspective on the concept of tipping point in the climate context, see Russill (2015).

- Human activities are interfering with the system Σ such that decisions taken within a "political time horizon" ($T_P > 0$) can determine whether the critical value for the control ρ_c is reached.
- The time to observe a qualitative change plus the time to trigger it lie within an "ethical time horizon" (T_E).
- A significant number of people care about the fate of the component Σ, because it contributes to the overall mode of operation of the Earth system (such that tipping it modifies the qualitative state of the whole system), it contributes significantly to human welfare (such that tipping it impacts on many people), or it has great value in itself as a unique feature of the biosphere.

Prominent examples of possible future policy relevant tipping elements considered in Lenton et al. (2008) include the Greenland and West Antarctic ice sheets, the Atlantic meridional overturning circulation (AMOC), the Arctic sea ice, the El Niño-Southern Oscillation (ENSO), the Asian and West African monsoons as well as the Amazon rainforest.[12]

Although closely related, there are several ways in which this characterization of tipping element (and tipping point) is distinct from (and not equivalent to) both the physical notion of abrupt climate change and the mathematical notion of bifurcation (discussed in sections 2 and 3 respectively). In particular, the definition (TE) emphasizes the occurence of a qualitative change rather than the abruptness of the change: indeed, (TE) includes cases "where the transition is slower than the anthropogenic forcing causing it" (Lenton et al. 2008, 1786). In other words, a tipping element may not involve an abrupt change in the sense of (ACC-2) (see section 2), whereas the latter always involves a tipping point ('threshold')—in this sense, the notion of tipping point is more general than the notion (ACC-2) of abrupt climate change (it is also more general in the sense that it is not restricted to the climate system, but concerns the Earth system more largely). Furthermore, the definition (PRTE) of a policy relevant tipping point also encodes the impact considerations of the definition (ACC-1), but makes explicit (some of) the subjective aspects involved in these notions (e.g. through the choice of the political time horizon T_P and the ethical time horizon T_E), to some extent easing transparent communication and public debate.

It is also important to note that, in principle, the notion of tipping element need not be restricted to equilibrium properties,[13] and so may not be characterisable in terms of bifurcation theory for autonomous dynamical systems. For instance, a tipping element may depend on the rate of change of some parameter, such that the (non-autonomous) dynamical system remains far from equilibrium (permafrost thawing is sometimes considered as possibly involving positive feedbacks due to decomposition that may lead to such a rate-dependent tipping, called 'compost-bomb', see Luke and Cox 2011).

Ashwin et al. (2012) actually distinguish three kinds of tipping mechanisms in open (i.e. non-autonomous) systems, namely bifurcation-induced tipping ('B-tipping'), noise-induced tipping ('N-tipping') and rate-induced (or rate-dependent) tipping ('R-tipping'). Here is a recent fairly intuitive characterization of these different tipping mechanisms (Ghil and Lucarini 2020, 56):

- B-tipping: slow change in a parameter leads to the system's passage through a classical bifurcation.
- N-tipping: random fluctuations lead to the system crossing an attractor basin boundary.

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[12] See also for instance the list of tipping elements (and tipping points) discussed in the IPCC Special Report on the impacts of global warming of 1.5°C (SR15), IPCC (2018, ch. 3).

[13] See the Appendix 1 of the supporting information to Lenton et al. (2008).

- R-tipping: because of rapide changes in the forcing, the system loses track of a slow change in its attractors.

In several models, the Atlantic meridional overturning circulation (AMOC) is associated with a bifurcation-induced tipping point (Dijkstra and Weijer 2005). In contrast, on the basis of ice-core record, the Dansgaard-Oeschger events, which involved abrupt warming during the last ice age, are generally considered as being noise-induced (Ditlevsen and Johnsen 2010). The 'compost-bomb' mentioned above is an example involving a rate-induced tipping mechanism.

The mathematical details behind these various tipping mechanisms are not relevant here. What is important in our conceptual perspective is that the noise-induced and rate-induced tipping points may not involve any bifurcations in the sense of classical bifurcation theory. For instance, in the case of a rate-induced tipping (R-tipping), there is no critical parameter value at which the system undergoes a bifurcation; rather, there may be a critical rate of change for a relevant (time-dependent) parameter. It therefore seems that the notion of tipping point cannot be fully captured by the standard notion of bifurcation, and it is argued in the climate or Earth system context that the former is more general than the latter (Lenton et al. 2008, Bathiany et al. 2016, Ghil and Lucarini 2020). More precisely, Ghil and Lucarini (2020, 56) claim that the notion of tipping point "generalize[s] the bifurcation concept in the context of open systems that are modeled mathematically by NDS [non-autonomous dynamical systems] or RDSs [random dynamical systems]", although Ashwin et al. (2017, 2186) note that "[t]here seems to be no universally agreed rigorous mathematical definition of what a tipping point is" and that a "a tipping point in a real non-autonomous system will typically be a mixture of these effects [B-, N-, R-tipping] but even in idealized cases it is a challenge to come up with a mathematically rigorous and testable definition of 'tipping point' "—beyond the rather phenomenological characterization (TE) above.

To some extent, these technical aspects of tipping points find an echo in the wider debate about the notion itself, as we will see in the next sections.

5 Tipping points: scientific relevance and uncertainties

For a bit less than two decades now, the notion of tipping point is getting increasing prominence and visibility in climate and Earth system science as well as in climate change communication (Russill and Nyssa 2009, Russill 2015). At the same time, various types of criticisms and worries related to the notion have emerged. The main issues can be divided in three broad categories. First, there are worries about the scientific relevance of the notion, in particular in the face of the deep uncertainties involved. Second, some critics have argued that the notion of tipping point may be unhelpful and even confusing for the purpose of climate change communication. Third, general concerns have been raised from the social science perspective. These issues touch important epistemic and methodological aspects of tipping points (and abrupt changes) in the climate and Earth systems, so we will consider these three categories in turn,[14] starting in this section with the worries related to scientific relevance and uncertainties.

Regarding scientific relevance, a central issue concerns the (scientific) novelty of the concept of tipping point (in the climate context), that is, the extent to which it really captures novel features of the climate system (or of the Earth system) that are not already adequately described by other well-established physical and mathematical concepts, such as abrupt climate change or those of bifurcation theory. The point is that if tipping points are "old wine in new bottles", as the

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[14] Of course, as we will see, some of these issues are clearly related; e.g., issues about climate change communication are linked to worries about scientific relevance and uncertainties.

editors of *Nature* put it (2006), then it needs to be clearly acknowledged that the main purposes of introducing this new concept in climate (and Earth system) science are extra-scientific (e.g. related to policy-making and climate communication).[15]

Now, the fact that the notion of tipping point in the climate context is intended to have some policy and communication relevance is actually explicit in the very definition of policy relevant tipping elements (PRTE) in section 4 above. Relatedly, possible cascading or domino effects linking the main tipping elements of the climate and Earth systems are clearly put forward in a risk management perspective, that is, in view of adequate policy-making (Steffen et al. 2018, Lenton et al. 2019).

However, having some policy and communication relevance does not prevent a concept to have its own scientific legitimacy, and indeed the notion of tipping point is often presented as such in the climate and Earth system literature. In this context, as we have highlighted in the last section, in both the phenomenological (Lenton et al. 2008) and the more mathematical (Ashwin et al. 2012) perspective, the concept of tipping point is aimed to generalize standard notions such as abrupt change and bifurcation.[16]

The concrete scientific relevance of the notion of global tipping point—that is, a tipping point for the climate system or for the Earth system as a whole, possibly induced by cascading effects[17]—has also been more specifically put into question. For instance, in a reply to Crucifix (2020) on the general relevance of the tipping point concept, Annan (2020) writes: "there is no scientific reason to believe there is a particular tipping point or threshold demarcating a safe space with low harm, from a catastrophic collapse of civilisation".[18] It is not the aim of this contribution to discuss the current scientific support to the possibility of a global tipping point in the climate or Earth system; suffice it to say that this issue is clearly distinct and has no direct bearing on the scientific relevance of the concept of tipping point itself (moreover, local tipping points in the Earth system do not necessarily involve any global, planetary tipping point). However, the concerns about the notion of global tipping point are linked to the issue of the deep uncertainties that are involved when it comes to tipping points in the climate or Earth system—both at the local and global levels.

Indeed, while some key positive feedbacks for certain tipping elements are rather well identified (e.g. salt-advection feedback in the case of the AMOC), there are still many deep uncertainties about tipping mechanisms and their interactions. Moreover modelling tipping elements is extremely challenging; to some extent, some of the standard challenges faced by climate modelling in general (see Frigg et al. 2015 for a philosophical overview) are exacerbated in the context of tipping points. For instance, contemporary observational data may have limited relevance for evaluating the adequacy of climate models to encode (future) abrupt changes and tipping points, since contemporary observational data may not contain any relevant abrupt changes and tipping points (this is a specific aspect of a general issue about climate model evaluation, see e.g. Parker 2009 and Baumberger

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[15] See the discussion in Russill and Nyssa (2009); of course, the relevance of the tipping point concept for these extra-scientific purposes also needs to be carefully scrutinized (see next section).

[16] In contrast, it is interesting to note that the climate scientist Michel Crucifix explicitly considers that the relevance of the notion of tipping point is best understood in view of adequate climate risk management and policy-making ("far-thinking climate governance"), that is, that it is best considered as a conceptual (and communication) tool for drawing attention to certain mechanisms in the climate and Earth system with far-reaching environmental and socio-economical consequences (the physical mechanisms being themselves described by other technical concepts such as bifurcation)—see Crucifix (2020).

[17] For instance, in a publication that attracted much attention, Steffen et al. (2018) describe how such a global tipping point in the Earth system (or "planetary threshold") could drive the Earth system to a "Hothouse Earth" state.

[18] In their paper aiming to raise awareness to the possibility of cascading tipping points in the climate system, Lenton et al. (2019, 595) similarly note: "[s]ome scientists counter that the possibility of global tipping remains highly speculative."

et al. 2017). This latter point further highlights the crucial importance of the paleoclimate data when it comes to abrupt changes and tipping points[19]—even if paleoclimate data involve their own challenges. A further difficulty for modelling tipping points is that climate models tend to be calibrated to be too stable: for example, those containing large abrupt changes tend to be discarded from multimodel ensemble studies such as the Coupled Model Intercomparison Project, currently in Phase 6 (CMIP6)—see the discussion in Drijfhout et al. (2015).[20]

One can distinguish two different methodological stances with respect to the deep uncertainties surrounding abrupt climate changes and tipping points (Bathiany et al. 2016, §6): the first, "bottom-up", approach aims at modelling abrupt changes and tipping points with "as much realism as possible", whereas the second, "top-down", approach explores the "possibilities of tipping points and devise methods to analyse and categorize them". In many cases, the skeptical and critical attitude with respect to tipping points actually tends to focus on the first approach only, which is often considered as the standard (or default) strategy in climate science more broadly.

The second approach relies on a more qualitative perspective, e.g. in the sense of dynamical systems theory. Indeed, as we have seen above, such a qualitative perspective allows one to meaningfully investigate abrupt changes and tipping points in the climate and Earth systems, even given the deep uncertainties that are involved about the relevant underlying (physical, biogeochemical, ...) processes. For example, the tipping behaviour can be studied in low-dimensional conceptual models (e.g. using bifurcation theory) if it is dominated by only a few positive feedbacks (see section 3).[21]

Of course, as Bathiany et al. (2016) stresses, these two methodological perspectives need not stand in opposition and are actually best conceived as complementary.[22] Indeed, they may well be fruitfully combined: for instance, stability properties of complex climate models can be studied using tools from bifurcation theory. These latter (together with statistical methods) also play a central role when it comes to the crucial issue of finding generic 'early warning indicators' of abrupt changes and tipping points, such as 'critical slowing down', which involves, very roughly, some slower rate of recovery from perturbations as a bifurcation is approached (for an overview in the climate context, see Lenton 2011; this is an important topic of on-going research, and there is a debate about whether and to what extent all types of tippings, in particular N- and R-tippings, allow for generic early warning indicators, see e.g. Ditlevsen and Johnsen 2010 and Ritchie and Sieber 2016). These indicators can typically be applied to complex model outputs, but also directly to observational data, such as paleorecords.[23]

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[19] In particular, paleoclimate data, such as those about the Dansgaard-Oeschger events, are often put forward as a strong motivation for taking seriously abrupt changes and tipping points in the climate and Earth systems.

[20] It is also interesting to note that Drijfhout et al. (2015)'s systematic investigation of the CMIP5 climate models for abrupt changes reveals that the detected abrupt events are "model-specific", thereby illustrating the large uncertainties that are involved.

[21] For instance, Wunderling et al. (2021) is a very recent example of such a qualitative perspective applied to the study of the interactions among various Earth system tipping elements.

[22] Concerning the possible opposition between these two methodological approaches here—and possibly leading to a dismissal of the qualitative, dynamical systems theoretic perspective—Bathiany et al. (2016, 22) make an interesting parallel with the debate about catastrophe theory in the 1970s and argue that "[g]iven the great deal we have learned since then, the scientific community should not make the same mistake twice".

[23] Again, this nicely illustrates the complementarity of the two methodological stances discussed above, as highlighted by Thompson and Sieber (2011, 5): "[a]n alternative to the *model and simulate* appoach [...] is to realize that mathematically some of the climate-tipping events correspond to *bifurcations* [...], and then to use time-series analysis techniques to extract precursors of these bifurcations directly from observational data [...]", "bifurcation predictions directly from real time series will be a useful complement to modelling from first principles because they do not suffer from all the many difficulties of building and initializing reliable computer models."

6 Communicating about tipping points

As we have mentioned in the previous section, and as detailed in Russill and Nyssa (2009) and Russill (2015), the notion of climate tipping point has central policy and communication dimensions. In this context, a recurrent criticism is that the concept of climate (and Earth system) tipping points—in particular global ones—is too alarmist, possibly leading to a loss of credibility of the scientific community and to inadequate reactions such as fatalism or cynicism (see, e.g., Nature 2006, and more recently Annan 2020). Besides the specific communication issues (see Russill and Nyssa 2009 for a discussion), which are not the main focus here, we would like to highlight an interesting analogy with the debate about the appropriate methodology and the role of non-epistemic (e.g. social, ethical) values in the context of extreme event attribution.

It has been convincingly argued that the methodological differences between, on the one hand, the standard probabilistic approach to extreme event attribution (in terms of the fraction of attributable risk) and, on the other hand, the recent storyline approach to extreme event attribution (which aims at identifying "physically self-consistent unfolding of past events, or of plausible future events")[24] reflect different attitudes towards risk, and that choosing between these different attitudes is not a purely scientific matter, but involves non-epistemic values (Lloyd and Oreskes 2018, Winsberg et al. 2020). By its very focus on causal stories, the storyline methodology is prone to type I errors (or 'false positives'), whereas the probabilistic risked-based methodology is prone to type II errors (or 'false negatives'), by averaging out the effect; preferring to avoid one type of error rather than the other involves non-epistemic values and preferences. Lloyd and Oreskes (2018) convincingly argue that "there is a strong bias in the scientific community" (317)—and in the climate science community more specifically—against type I errors. In particular, the critique of 'alarmism' that has been raised against the storyline approach largely relies on such a bias. One of the factors for this bias that Lloyd and Oreskes (2018) identify is the community norms of rationality, according to which "more conservative claims tend to be viewed as more rational—and therefore more scientific—than less conservative ones" (317); however, such norms are not necessarily epistemically justified (to say the least), and actually need to be openly debated and communicated.

Now, the interesting point for us is that, in many ways, the above concerns about tipping points also seem to largely rely on a similar bias. Indeed, the critique that considerations about tipping points lead to undue alarmism mainly focuses on the danger of making type I errors, and often completely neglects the twin danger of type II errors. As Lloyd and Oreskes (2018, 318) note, the "point here is not that one set of risks is necessarily worse than another, but rather than climate scientists have been asymmetrical in their concerns". In this perspective, what is required is an open communication about tipping points and the epistemic limitations that are involved, as well as an open debate about the different attitudes towards risk that can be adopted in this context.[25]

In order to facilitate such a debate and to balance the above mentioned asymmetry, it might be fruitful to apply the storyline methodology to climate (and Earth system) tipping points. This methodology is indeed in no way restricted to the attribution context and can also be applied to the characterization of future climate change, in particular in cases involving strong uncertainties that may weaken the relevance of probabilisitic projections (such as for certain regional climate change projections, extreme events and, of course, tipping points). Indeed, instead of providing (probabilistic) predictions (or projections), storylines aim to investigate plausible climate change futures, that is, to "explore the boundaries of plausibility" as Shepherd et al. (2018, 566) put

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[24] Shepherd (2019, 2).

[25] This clearly concerns both types of errors; for instance, the worries concerning wrongly setting 'climate deadlines' should be seriously taken into account (Asayama et al. 2019), as should be the consequences of missing cascading tipping effects (Lenton et al. 2019).

it (see also Shepherd 2019, who advocates a "reframing of the climate risk question from the prediction space into the decision space"). For instance, tipping point storylines would investigate plausible climate change futures involving climate (or Earth system) tipping points, e.g. articulating "physically self-consistent unfolding of [...] plausible future events" exploring the consequences of crossing tipping points, without necessarily assigning any probabilities. We suggest this is a much-needed line of research that may help to navigate the tension between the possible huge impacts and the deep uncertainties linked to climate (and Earth system) tipping points and abrupt changes—for recent steps in this direction, see for example Ritchie et al. (2020), who study plausible impacts of the collapse of the AMOC on land use and agricultural production in Great Britain.[26]

7 Tipping points in the Anthropocene: the social science perspective

The notion of climate and Earth system tipping point has central policy dimensions in the sense that it aims to influence the societal and political response to the climate (and environmental) issues (which it helps to frame as an "emergency", see Lenton et al. 2019). In this line of thought, there are also considerations for identifying and inducing 'positive' (in the broad sense of 'desirable' in view of managing the climate challenge) tipping mechanisms in various socio-ecological systems (e.g., see recently Lenton 2020 and Otto et al. 2020). This is a rather natural move, considering the fact that the very concept of tipping point has emerged from studies on social systems (about racial segregation) in the first place (on the origins of the notion, see Russill 2015; for a review of the literature on social and socio-ecological tipping points, see Milkoreit et al. 2018).

These social and policy-related aspects of tipping points have given rise to a broad but constructive social science critique; this latter is interrelated with epistemological and methodological considerations and can greatly enrich the philosophy of science perspective adopted in this contribution—to this effect, we briefly review some elements of this critique in this section.[27]

In a first approach, the very fact that the same concept of tipping point is applied to a large variety of very different natural (physical) and social contexts leads to the worry that crucial differences between physical and social processes may be blurred (Milkoreit et al. 2018, §7, Russill and Nyssa 2009, §11)—in particular, as a result, the specificities of the various social contexts and processes may simply be left out of the picture. This may in turn lead to an impoverished and potentially biased understanding of the relevant social features and dynamics underlying social tipping points.

More generally, in the Earth system science perspective, the concept of tipping point in the climate and Earth systems (together with the related notion of planetary threshold) is closely linked to the concept of Anthropocene. This latter is typically defined as a "new geological epoch in which humans are the primary determinants of biospheric and climatic change" (see Steffen et al. 2020, 59, where the concept of Anthropocene is explicitly described as arising from Earth system science), and there is a growing consensus on its scientific relevance.

However, the concept of Anthropocene, as currently articulated in the scientific literature, is also critically considered by some parts of the social sciences and the humanities.[28] Indeed, de-

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[26] Very recently, see also Wunderling et al. (2021, 602), who view their study of the interactions among Earth system tipping elements as "a hypotheses generator that produces qualitative scenarios (rather than exact quantifications or projections) that can then be further examined by more process-detailed Earth system models."

[27] Indeed, in many ways, this section can be understood as a call for more interactions between philosophy of science and social sciences (which are here broadly construed) on climate and environmental issues.

[28] It is clearly beyond the scope of this brief section to do full justice to the richness of the social science critique here; for more detailed discussions, see, e.g.,Palsson et al. 2013, Lövbrand et al. 2015 and Bonneuil and Fressoz 2016.

spite the fact that the concept of Anthropocene centrally involves human and social dimensions, these latter tend to be neglected, and the Anthropocene narrative is often dominated exclusively by the natural science—in particular, Earth system science—perspective. As a consequence, "[t]he anthropocenologists' dominant narrative of the Anthropocene presents an abstract humanity uniformily involved—and, it implies, uniformily to blame" Bonneuil and Fressoz (2016, ch.4). It is precisely such an abstraction (the "humans") that underlies the above typical characterization of the Anthropocene—at least without further qualifications. Similarly, Lövbrand et al. (2015, 214) warn that "[w]hen the complex environmental challenges of our times are accounted for in aggregated terms, we lose sight of the situated conflicts, warped distribution of wealth and unequal power relations that engine 'the great acceleration'", which denotes a post-World War II strong accelerating trend in a series of socio-economic and Earth system indicators.

This analysis also points to the fundamentally global nature of the Earth system science perspective and in particular of the related Anthropocene narrative, which runs the risk to render "the human beings invisible, both as agents and victims of environmental destruction" (Lövbrand et al. 2015, 216). Both the human impacts (including responsabilities) and their consequences (including vulnerabilities) are heterogenous and need to be differentiated in several ways (e.g. taking into account their geographical and social distributions). The worry is that this heterogeneity and these differences may not be accounted for in the global Anthropocene narrative. At the heart of the difficulties here lies a tension between this global perspective and the local scale at which people get impacted (this tension has been nicely highlighted by Shepherd and Sobel 2020 in the context of climate science). In a completely analogous way, this tension also directly affects the notions of Earth system tipping point and planetary threshold, which can be useful notions in a global perspective (e.g. for discussing the consequences of some cascading effects, see Lenton et al. 2019), but, at the same time, which can hide the vast heterogeneity of what these notions may involve at the local scale (e.g. in social, political, economical terms).

These homogenizing effects also need to be seriously considered in the context of the recent proposals for deliberately triggering positive social tipping points (e.g., see recently Lenton 2020, Otto et al. 2020). As we have already mentioned above, the fact that the same concept of tipping point[29] is used for both natural (physical) and social systems should not mask the differences between the relevant underlying physical and social processes in both contexts.[30] These differences may not prevent the useful application of the same mathematical and conceptual tools (e.g. for early warning signals), but their potential limitations in the social context should be more systematically explored and explicitly highlighted (similar considerations are also put forward in the conclusion of Milkoreit et al. 2018).[31]. Indeed, recently, there have been first steps in this direction within the Earth system science community. For instance, Winkelmann et al. (2020) identify several key differences between social and climate tipping processes, such as the presence of (human) agency, the structure and complexity of social networks, and the relevant temporal and spatial scales.

More generally, from the social science (and political ecology) point of view, a central worry with the strategy of social tipping interventions—and more globally, with the larger conceptual framework of planetary stewardship (Steffen et al. 2018)—is that it may completely overlook the

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[29] Recent formalizations in the literature of the notions of social tipping point (e.g., see Milkoreit et al. 2018) and social tipping element (e.g. relevant for decarbonization transformation, see Otto et al. 2020) are actually very similar to (and, in the latter case, even explicitly reply on) the standard definitions in the climate and Earth system context, see (TE) and (PRTE) in section 4 (see also Winkelmann et al. 2020).

[30] The very notion of 'positive' social tipping point can be ambiguous in the sense that there may be disagreement about what exactly is considered as 'positive' or 'desirable'.

[31] Of course, this also concerns the possible application of modelling and machine learning techniques in this context (e.g. see Donges et al. 2020).

plural and political nature of the underlying social mechanisms, rather favouring a normative narrative of an apolitical and purely scientific course of action. Such a narrative may then lead to "techno-managerial planning and expert administration at the expense of democratic debate and contestation" (Lövbrand et al. 2015, 217; see also Russill 2018, 256). This a serious concern that needs to be taken into account.[32]

8 Conclusion

This contribution provides a brief and (non-exhaustive) overview of some important epistemic and methodological issues in relation to abrupt climate changes and, more broadly, tipping points in the climate and Earth systems (including social tipping points with climate policy relevance). In particular, the concept of tipping point is connected to a number of different physical and mathematical notions, and as such it raises many technical, but also climate communication and social science issues. Within this framework, it seems therefore particularly important to be as explicit and precise as possible about the exact definition that is at work in a given context, about its purpose and its limitations.

Furthermore, the tension between the potential huge impacts and the deep uncertainties at the heart of (most of) the climate and Earth system tipping points (including local, regional tipping points and their interactions) highlights the relevance of a qualitative ("top-down") perspective in complement to the standard (and sometimes exclusive) modelling ("bottom-up") strategy. Such a qualitative perspective can be articulated in different ways, e.g. in the sense of dynamical systems and bifurcation theory or by devising physical storylines involving tipping points (in contrast and in complement to the usual probabilistic projection strategy).

Within the framework of the climate and environmental challenge, a better understanding of abrupt changes and tipping points in the climate and Earth systems (including local, regional ones) is crucial—in particular in view of avoiding negative (i.e. undesirable) tipping points, but possibly also in view of inducing positive (i.e. desirable) ones. Given the plural nature of the challenge and the deep intertwining between natural and social systems (at many different, including epistemological, levels), which is at the heart of the notion of Anthropocene, this understanding needs to be truly interdisciplinary, e.g. involving climate and Earth system science as well as philosophy and social sciences.

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[32] The dialogue with the social sciences and the humanities promoted by parts of the Earth system science community constitute important first steps in this direction, see e.g. Otto et al. (2020, 2362).

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