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Climate tipping points and expert judgment

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Abstract

Expert judgment can be seen throughout climate science and even more prominently when discussing climate tipping points. To provide an accurate characterization of expert judgment we begin by evaluating the existing literature on expertise as it relates to climate science as a whole, before then focusing the literature review on the role of expert judgment in the unique context of climate tipping points. From this we turn our attention to the structured expert elicitation protocols specifically developed for producing expert judgments about tipping points. We highlight that expert elicitation is not only used for the quantification of uncertainty in this context, but also for the very identification and characterization of tipping points and their interactions, making expert judgment in itself a genuine scientific output. The central role of expert judgment in this domain raises several epistemic issues that require careful attention. Among other topics, we discuss the relationship between expert judgment and modeling, as well as the nonepistemic values that are involved in the production of expert judgments, highlighting how the elicitation protocols can be used to manage these values. In the perspective of climate change, clarifying the epistemic foundations of expert judgment in this context can help to navigate the epistemic situation between self-defeating alarmism and blind dismissal, thus contributing to a better understanding of the challenges related to climate (and Earth system) tipping points.

This article is categorized under:

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climate and earth system modeling, climate and earth system tipping points, expert judgment and elicitation, nonepistemic values, uncertainty

1 | INTRODUCTION

In the context of climate and environmental challenges, tipping points in the climate and Earth systems have gained increased prominence in recent years. This is not only in climate change communication (Russill & Nyssa, 2009), but also in the scientific community itself—in particular, tipping points constitute a "cross-cutting theme" and are identified as one of the "Reasons for Concerns" in the latest (sixth) assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC, 2021).

However, from a climate risk perspective, the scientific discussion on tipping points faces a tension. On the one hand, many climate tipping points are associated with huge potential impacts on human and natural systems: for instance, the collapse of major ice sheets or abrupt changes in monsoon systems could dramatically affect a significant proportion of the world population (Lenton et al., 2008). Moreover, interactions among climate tipping points may lead to cascading effects with possible drastic consequences for the entire Earth system (Steffen et al., 2018); indeed, it is argued that such considerations help "to define that we are in a climate emergency" (Lenton et al., 2019).

On the other hand, there is high (as well as deep) uncertainty (see Box 1) surrounding tipping points and making quantitative statements about tipping points is challenging. Capturing possible tipping behavior with climate models is particularly challenging for several reasons (McNeal et al., 2011). First and foremost, within the model itself, crucial (e.g., feedback) mechanisms may be missing (or ill-understood). Also, climate models rely on observational data (e.g., for tuning, for evaluation) that may not encode any tipping points. Another pragmatic issue concerns the fact that assessing "low likelihood," complex events such as crossing tipping points using (complex) climate models requires important computational resources (e.g., many long simulations), which may not be easily available. Finally, tipping behavior in the climate models may fall prey to a selection bias: simulations displaying abrupt changes and unstable configurations tend to be discarded (Drijfhout et al., 2015; Valdes, 2011).

One standard way to manage this tension is to appeal to expert judgment, over and above climate modeling outputs. Indeed, expert judgment plays a central role in the scientific literature on climate and Earth system tipping points: most of the papers on the topic rely on expert elicitation for the identification and characterization of the considered tipping points and their interactions. More precisely, papers investigating Earth system tipping points and their interactions very often refer to one of the few papers on the topic where such an expert elicitation has been carried out, such as, for example, Lenton et al. (2008) and its companion paper Kriegler et al. (2009) (as recent examples, Cai et al., 2016 study the policy implications of five interacting tipping points as identified in these papers, and Wunderling et al., 2021 investigates domino effects among interacting tipping points relying on the expert elicitation conducted in Kriegler et al., 2009).

Now, the central role of expert judgment in the context of tipping points raises a number of epistemic issues about its nature and status. Within this framework, expert judgment is actually a generic expression that encompasses different aspects, which are often somewhat implicit in the literature. The aim of this paper is to review the main epistemic issues that are related to expert judgment in the context of climate and Earth system tipping points.

Clarifying the epistemic foundations of expert judgment on climate and Earth system tipping points is connected to other important epistemic issues in climate science, such as the status of climate modeling and the role of nonepistemic values and other subjective elements in climate science (Pulkkinen et al., 2022). In the perspective of climate change,

BOX 1 HIGH VERSUS DEEP UNCERTAINTY

Uncertainty, as a concept, has been applied to many different fields and has taken on different meanings. Here, we take uncertainty to be an epistemic state (of an individual or a group) characterizing some lack of (adequate) knowledge about a target system, where the level of uncertainty may or may not be quantifiable (e.g., probabilistically). In this perspective, a distinction can be made between high and deep uncertainty.

High uncertainty is the epistemic situation where the state of knowledge is relatively more incomplete/inadequate when compared to other cases (e.g., with low uncertainty) in the domain, but where some level of agreement still obtains among experts about the system model and the alternative outcomes or scenarios.

By contrast, deep uncertainty captures the epistemic situation where the state of knowledge is such that experts know or can agree on neither the appropriate system model nor the alternative outcomes or scenarios.

The context of climate tipping points involves cases of high uncertainty as well as cases of deep uncertainty.

However, there is no uniform terminology in the literature, see for instance Walker et al. (2013), Hansson and Hirsch Hadorn (2016) and Hansson (2022) for various classifications of different types of uncertainties within the framework of decision theory. It should also be noted that the IPCC does not distinguish between high and deep uncertainty (2021, ch. 1).

such a clarification can help to navigate the epistemic situation between self-defeating alarmism (or "deadline-ism," see Asayama et al., 2019) and blind dismissal, thus contributing to a better understanding of the challenges related to climate and Earth system tipping points.

We begin by introducing expert judgment in general terms as it relates to uncertainty, highlighting the current literature on expert judgment in climate science before focusing our attention on expert elicitation for claims surrounding climate tipping points (Section 2). We then turn to the epistemic foundations of expert judgment about climate tipping points, in particular articulating the relationship between expert judgment and modeling and discussing the extent to which expert judgment can be considered as a genuine scientific output in this context (Section 3). We conclude in Section 4.

2 | EXPERT JUDGMENT AND UNCERTANITY

To begin, we take, as a general definition, expert judgment as the claims of experts, made under some level of uncertainty, either within the individual's domain of expertise or made on the discipline itself. Much of the general discussion on subjective expert judgment and uncertainty has focused on this later feature of the definition, using expert judgments to support the decision making of nonexperts, usually policy makers, through the evaluation of the current state of the discipline.[1] This has resulted in a robust discussion surrounding the uncertainty quantification and communication between experts and nonexperts, in fields with high uncertainty and/or with high potential impact, like the nuclear and aerospace industries. Within these industries this conversation generally focuses on uncertainty in the context of "assessing risks associated with rare or unobserved catastrophic events" (Cooke, 1991, p. 19). Unsurprisingly, a similar focus on the evaluation of an expert's ability to assist decision making under uncertainty has come to the forefront of the discussion of expertise in the context of climate science as well (Cooke, 2015). In this section, we begin by providing an overview of the field, highlighting the existing discussions of expertise in climate science before then moving to expert judgment specifically related to tipping points. This discussion will focus on the structured elicitation protocols precisely created for generating claims about climate and Earth system tipping points and their interactions.

2.1 | Expert judgment in the climate science context

This discussion of expertise and decision making in the climate science context has been investigated along two main veins––the evaluation of experts, and the quantification of uncertainty, with special attention given to the framework developed by the IPCC for assessing and communicating uncertainty within its assessment reports. In what follows we outline these two main, and in some ways interconnected, veins and provide the necessary context for further discussions of expertise used specifically in reference to claims about tipping points in the climate and Earth systems.

The first vein, the evaluation of experts, has utilized the vast social epistemology literature on notions of expertise. Within this general literature the evaluation of expertise takes on many forms, defining what it means to be an expert, principles of expertise, and expert disagreement, as well as others.[2] Within the climate science context, the discussion has focused on the principles of expertise or the criteria nonexperts have for evaluating expertise.[3] These criteria have been used to evaluate potential expert disagreement (Coady & Corry, 2013, ch. 3), discussing how non experts should behave or what they should believe when there is apparent disagreement among experts. What is clear from these discussions is that a goal of these criteria is to remove (or at least mitigate) the subjective elements of expertise from the scientific practice.[4] This effort can be seen in the supporting evidence criterion, which requires the expert to make explicit arguments based on "objective evidence," but when subjective expert judgment is taken as evidence (as in the climate science context) this criterion may not be satisfied (Martini, 2014). In these cases, there may be a large set of unconnected lines of background information which the expert synthesizes into a single judgment and may not be able to explicitly describe the synthesis in the form of an argument (Martini, 2014, p. 7). Thus, entirely removing subjective elements from expert judgment may actually not be practically possible––and maybe not even desirable.

Within the second vein, the questions regarding uncertainty are generally in relation to the assessment of model uncertainty using expert judgment. Due to structural features and the limited number of models available, ensembles of models are insufficient to properly span uncertainty ranges in the climate context, and expert judgments are then required to re-assess these uncertainty ranges (Thompson et al., 2016). Thus, it has been suggested to utilize expert judgment to ensure "that areas of uncertainty poorly captured by models are better represented" (Aspinall, 2010). This practice of using expert judgment for weighting and evaluating model uncertainty can be seen in the assessment reports by the IPCC. Take the following example from the *Summary for Policy Makers* from the fifth assessment report AR5 (IPCC, 2013): where the considered model range for projections of global mean surface temperature change is 5%–95%, this range is assessed as *likely* rather than *very likely*, which would be the assessment corresponding to a 90% likelihood interval (IPCC, 2013, p. 23, Table SPM.2, footnote c). It is stated that this practice of downgrading is done because various sources of evidence, including expert judgment, lead to the conclusion that the range of model outcomes does not adequately reflect the actual uncertainty involved (IPCC, 2013, §12.2). Similarly, the latest assessment report (AR6) acknowledges that while progress has been made there still does not exist a robust evaluation methodology for weighting multimodel projections resulting in the inclusion of expert judgment and thus follows the approach of the previous report (i.e., AR5), stating that one should interpret the "CMIP6 5-95% ensemble range as the *likely* uncertainty range" (IPCC, 2021, box 4.1).

In particular, probability distribution functions (PDFs) can serve as a representation of uncertainty on a range of outcomes, with full PDFs specifying weights to each possible outcome and partial PDFs representing a range of possible outcomes being specified. One proposed way of evaluating the appropriateness of using PDFs in the climate context, among other options, has been through the use of expert judgment. For instance, Katzav et al. (2021) recently argue that in specific circumstances expert judgment can compensate for limited data/theory for using PDFs, while acknowledging that this use does not come without its concerns: they focus on two key concerns, the construction of the ensemble of models and the way the ensemble output is related to the real world (Katzav et al., 2021, §3.3). As the field currently stands, expert judgment will continue to play a role in the re-assessment of model uncertainty whether that is in the downgrading of the ranges or in another capacity.

Finally, the IPCC's uncertainty framework has been discussed with some attention given to the use of expert judgment within this framework. In brief, the IPCC utilizes two metrics for the communication of uncertainty, a confidence level and a likelihood scale. Take the following example from the IPCC's latest assessment report (AR6), where it is stated that "[g]lobally averaged precipitation over land has *likely* increased since 1950, with a faster rate of increase since the 1980s (medium confidence)" (IPCC, 2021, p. 5). This sentence contains the two metrics the IPCC uses to assess uncertainty, the calibrated language of likelihood (in italics), and a level of confidence (at the end of the statement in the parentheses). The likelihoods express a probabilistic estimate of the outcome of an event and can be based on, among other things, the "elicitation of expert views" (Mastrandrea et al., 2010, p. 3). The confidence metric refers to the entire statement under consideration and is based on the synthesis of the authors' judgment about the validity of the findings (Mastrandrea et al., 2010). Thus, these metrics, in varying degrees and complementary ways, utilize expertise to communicate the degree of certainty in the findings outlined in the IPCC's assessment report.[5] A formal evaluation of the IPCC's framework for assessing and communicating uncertainty has been done by Bradley et al. (2017). Within the many suggestions given, one example was with respect to the calibration of the confidence levels and the need to further develop the elicitation protocols for expert judgments (Bradley et al., 2017, section 6). Others have suggested that providing more "pliable language" will allow for easier use of the framework across diverse scientific disciplines related to the climate and allow for greater ease in resolving expert disagreement (Helgeson et al., 2018). Some of the challenges of utilizing these uncertainty metrics and a potential path forward have been discussed as well in Mach et al. (2017).

What has received much less attention in the discussion of expertise and expert judgment in climate science are tipping points in the climate and Earth systems. Issues regarding expertise in this context intersect both veins we have discussed, the evaluation of experts and the quantification of uncertainty. The question of who qualifies as an expert in relation to tipping points is nontrivial as the issues and fallout of potential tipping points requires interdisciplinary knowledge from potentially disjointed fields of research. Thus, identifying who should be included in the conversation is not a straightforward endeavor, especially from an Earth system science perspective or if human and social processes are to be included.

Additionally, we see the second vein, expert judgment used in the quantification of uncertainty, as playing a role in the discussion of tipping points. Indeed, as we have mentioned in Section 1, assessing tipping points with current climate models faces many challenges. There is a possible selection bias in modeling tipping points, with concerns being raised about the ability of complex models to accurately simulate threshold behavior for known abrupt changes in the past (Valdes, 2011). Furthermore, the "character, timing and location of abrupt events" have been found to be model-specific, illustrating the close relationship between the specific model and the model outputs as they relate to a given tipping point (Drijfhout et al., 2015). As a result, there is some uncertainty in the representational relationship between the model outputs and claims related to tipping points. Expert judgment is then crucial when evaluating the uncertainty ranges associated with climate and Earth system tipping points, and their interactions.

Furthermore, given their potentially huge impact, some tipping points are especially relevant for policy-making, that is, for crafting adequate mitigation and adaptation strategies (see Section 3.1). The quantification and communication of uncertainty around these events, for nonexpert policy makers, then comes to the forefront with the IPCC's uncertainty framework taking center stage. The framework is quite extensively used to discuss tipping points in the latest report AR6––in making claims such as "tipping points of the climate system, such as strongly increased Antarctic ice-sheet melt and forest dieback, cannot be ruled out (high confidence)" and "[t]he Atlantic Meridional Overturning Circulation is *very likely* to weaken over the 21st century for all emissions scenarios"––with both the likelihood language and confidence metric being utilized (IPCC, 2021, p. 26). However, how exactly to handle tipping points using the IPCC framework or even the extent to which this framework is useful for communicating the kind of (high or deep) uncertainties related to tipping points (and other "low-likelihood high impact" events) has been little discussed in the literature so far.[6]

There is something unique about tipping points in the sense that claims about tipping points and their interactions tend to more heavily rely on expert judgment than other features of climate science. Indeed, the difficulties to accurately model climate and Earth system tipping points have led to central questions about tipping points––what constitutes a tipping point, what are the known possible tipping points, what would be the effect of crossing a tipping point, how do different tipping points interact with each other––being answered in a way that heavily relies on expert judgment. Now, in order to articulate expert judgment in a systematic way in this context, structured elicitation protocols have been developed.

2.2 | Expert elicitation protocols for tipping points

In this section we focus our attention on the development of these formalized approaches or protocols for eliciting structured expert judgment. While there is not a standard definition of structured elicitation protocols agreed upon by the entire community, these protocols generally refer to a formalized methodology combining various steps to obtain the judgments of a group of experts, which are then aggregated with the goal of answering a question or set of questions about the domain or system (Hanea et al., 2021). These protocols have taken many forms, like the Delphi Method (Dalkey, 1969), Cooke's Model (Cooke, 1991), and the SHELF Protocol (Oakley & O'Hagan, 2016),[7] which have been used across a range of scientific disciplines, from determining training priorities for medical students (Viljoen et al., 2020) to assess extinction risk of subterranean aquatic species (Fitzgerald et al., 2021). What should be noted is that all of these methods utilize some form of a structured elicitation protocol for the formalization of expert judgments. This formalization is seen as a way to facilitate the quantification of uncertainty in a methodology that is reproducible, consistent and transparent (Oppenheimer et al., 2016). Ultimately, the development of structured elicitation protocols is seen as a major effort to minimize the concerns of subjective biases reducing the reliability of expert judgments (Aspinall & Cooke, 2013).

In the climate science context there has been a similar approach, focusing on formalized protocols for combining modeling efforts with expert judgments (Oppenheimer et al., 2016). The utilization of these structured expert judgments can be seen in a range of contexts within climate science: for example, for identifying the relative contributions to the uncertainty of global climate sensitivity (Morgan & Keith, 1995), for characterizing regional climate uncertainty (Dessai et al., 2018), for an assessment of future sea level rise (Bamber et al., 2019; Bamber & Aspinall, 2013), as well as others. We however are interested here in the elicitation protocols used in the context of climate and Earth system tipping points and their interactions. More specifically, we focus on the elicitation procedure in Lenton et al. (2008) and Kriegler et al. (2009) for generating and aggregating expert judgments, which is one of the main (and only) systematic expert assessment protocols for climate tipping points and their interactions.

Their methodology consists of a five-step elicitation procedure using two groups of experts. The first step of this procedure was the development of the questionnaire which would subsequently be completed by the experts participating in the study. This questionnaire was designed to be completed on a computer and have adaptive questions based on the answers given by the expert. As a result, in step two of the elicitation procedure, when the questionnaire was distributed to the first group, experts were asked questions first identifying potential tipping points, then comparing the tipping points they individually identified as well as the interactions between these tipping points, and to estimate probability bounds for the likelihood of triggering the tipping points they identified under three different scenarios. What should be noted is that within this elicitation protocol expert judgment is not only being used for the quantification of uncertainty around tipping points but also within the very identification of tipping points and their interactions.

Step three involved the distribution of the questionnaire to the second group of experts, this was done to have adequate coverage over the large domains required to understand tipping points. The responses of the questionnaire from the two groups of experts were then compiled in step four, anonymized and then analyzed. These responses were returned to all individuals involved and each expert was given the option to revise; however, it should be noted that the experts were not pushed to reach a consensus on any single tipping point or interaction. Step five then concluded the elicitation protocol with a final round of analysis of the revised submissions.[8]

During this analysis, in step five, the choice of method for the aggregation of probability intervals comes to the forefront, as there is no unquestioned approach for aggregating subjective probabilities, with each method having benefits and drawbacks. To account for this, multiple aggregation procedures were discussed and evaluated including, linear and logarithmic pooling, Nau's pooling rule and forced consensus pooling.[9] Ultimately, for the presentation of results linear pooling was selected over the other candidates. Linear pooled event probability, or in this case of probability intervals, consists of the weighted average of the experts elicited probabilities. What was unique however was the conception and application of expert weights. Given that there is no single well justified method for assigning weights to each expert within the pooling process, three different weight scenarios were utilized. These three scenarios allowed for variation among the uniform weights by the following scales, ±50%, ±100% and complete ignorance. By assigning expert weights in these three different ways, this methodology can better capture the uncertainty about expert weights and not randomly assign weights. Furthermore, in this context, linear pooling combined with these uncertainty scenarios about expert weights was statistically shown to be robust against outliers and the resulting interval encompassing the convex hull of the union of expert estimates, making it a conservative choice as well as being more intuitively accessible.

Additionally, in this protocol there were clear attempts to reduce common cognitive biases, as can be seen in the following two examples of overconfidence and anchoring. First, when an expert was asked a question for eliciting a probability, a hypothetical was also posited. This hypothetical consisted of a colleague situated 20 years in the future who would judge the work of the expert. This was done in an attempt to increase ambiguity aversion and produce higher/lower bound probability values with a larger range. As a result, the expert would err on the side of caution in relation to the claims they are making, instituting a bias towards type II error, or a false negative. This means for instance that experts would be more likely to underestimate the probability (or the higher bound probability value) for a tipping point, leading to increased conservatism within the judgments. Within the questionnaire, overconfidence was seen as being exemplified by narrow probability ranges, thus increasing the probability range was seen as a meaningful reduction in any overconfidence. Second, in order to overcome any anchoring bias, where one can have the tendency to interpret new information from the standpoint of old information, the questions surrounding the likelihood of triggering tipping points were phrased as negative statements rather than the commonly used positive framing. These attempts show a strong desire to remove (or at least "control") common biases and subjective elements (such as nonepistemic values) in the production of expert judgments through structured elicitation protocols.

These attempts to address (nonepistemic) values and biases through structured elicitation are, as previously discussed, largely seen as beneficial in improving the reliability of expert judgment. However, what remains clear are two things: (1) not all values are seen as problematic and (2) it is not possible to remove these subjective elements completely through elicitation protocols. Take the example just given with the attempt to remove overconfidence using the design of the protocol. By designing the protocol in this way, the aim is to remove the cognitive bias of overconfidence; however, in doing so the protocol tends to promote more conservative judgments. While this trade off may be seen as unproblematic because conservatism as a value is widespread throughout science, this nonetheless illustrates that not all values are seen as equal and that some, like conservatism, may actually be seen as beneficial or at the very least unproblematic in science.

This leads to the second point: it is not possible to remove all subjective elements through elicitation protocols. Aside from this type of tradeoff between different subjective elements of expertise, there also exists values hidden within the uncertainty quantifications produced through expert elicitation. These quantifications can be seen, in the Bayesian sense, as subjective probabilities where the assessed probability is considered as a degree of belief in line with the axioms of probability. The probabilities are relative to the set of background information, taking the form of, among other things, modeling efforts. It has been argued that the probabilities are then influenced by the nonepistemic values used in the development of models, given that the models serve, at least in part, as background information in the production of these probabilities (Parker & Winsberg, 2018). More will be said on this relationship between expertise and modeling in Section 3.3, but what should be noted is that there are values involved in the background information used during the elicitation. The role of nonepistemic values in climate science has been recently acknowledged in the latest IPCC assessment report AR6 which states that "[s]ocial values are implicit in many choices made during the construction, assessment, and communication of climate science information" (IPCC, 2021, 1.2.3.2). Thus, removing these values from the background information used in expert elicitation is easier said than done, as these values are implicit in the very construction of climate information.

In light of these two points above, expert elicitation protocols are then best understood as ways to manage the subjective elements and values that are involved, rather than attempts to remove them. We now turn to the nature of the expert judgments about climate tipping points, focusing on the epistemic and methodological issues they raise.

3 | THE NATURE AND STATUS OF EXPERT JUDGMENT ON CLIMATE TIPPING POINTS

This section focuses on the plural (or "holistic") nature of expert judgment on climate tipping points, and on its relationship to climate modeling; in this context, expert judgment is often used as a scientific output on its own, and the extent to which this is epistemically warranted requires careful attention. We start with the role of expert judgment in the general definition of a climate (Earth system) tipping point.

3.1 | Defining policy-relevant tipping points

Providing a precise general definition of the notion of tipping point in the climate system (or, more globally, in the Earth system) is a rather subtle question, in particular if nonequilibrium properties are considered.[10] For the purpose of this review, we do not need to enter into any technicalities and we pragmatically adopt a standard characterization in terms of a threshold (or critical parameter value) in an Earth system component (called tipping element) beyond which a small perturbation leads to some qualitative change in a crucial system feature within some time frame (Lenton et al., 2008; see also the very recent reassessment in Armstrong McKay et al., 2022).[11] Tipping points are naturally related to abruptness and irreversibility (or hysteresis), but they do not necessarily imply these notions in this general understanding.

It is important to note that, in order to identify the tipping points that are relevant from the point of view of policy-making, the above mentioned time frame needs to be specified in a way that makes climate decision-making relevant on human time scales.[12] Similarly, the qualitative changes involved in policy-relevant tipping points need to be significant for society (e.g., in terms of impact or value). These specifications require making normative judgments, thus explicitly involving nonepistemic (e.g., ethical, social) values. These judgments are crucial to the definition of (policy-relevant) tipping points, but they do not really constitute expert judgments made by climate or Earth system scientists qua experts (e.g., ethical questions are not within their domain of expertise); given their potential impact on society, it can be argued that these normative judgments and the nonepistemic values underlying them should actually be open to public debate.[13]

3.2 | The "holistic picture" of expert judgment

Current knowledge about climate and Earth system tipping points does importantly rely on expert judgments made by scientists from a number of domains. The most straightforward way in which expert judgment plays a role is in the very identification and characterization of the main Earth system tipping elements and their interactions through expert elicitation procedures such as in Lenton et al. (2008) and Kriegler et al. (2009) (see Section 2.2). In this context, a crucial feature of expert judgment put forward in the literature lies in its ability to link together different lines of evidence from different sources. This is explicitly emphasized in Kriegler et al. (2009, 5044): "This points to the strength of expert elicitations in providing a holistic picture of beliefs incorporating not only model results, but also insights from empirical data and theoretical considerations." For instance, expert judgments about the possible collapse of the Atlantic meridional overturning circulation (AMOC) within a given time frame does not only rely on outputs of various types of climate and Earth system models (from conceptual models to state-of-the-art CMIP models), but also on theoretical considerations about the main feedback mechanisms (e.g., salt advection feedback) as well as on paleoclimate data (e.g., Dansgaard-Oeschger events and Heinrich events during the last glacial period have been associated with abrupt changes in the AMOC).

The "holistic picture" provided by expert judgment clearly involves reviewing the relevant literature, but it is in general not conceived as the mere result of such a review. Within the framework of an expert elicitation about the impact of climate change on the AMOC, Zickfeld et al. (2007, p. 237) argue that elicitation methods are "based on the experts' synthesis of published literature and knowledge that is not explicit in the formal literature." As briefly touched on in Section 2.1, articulating precisely what this knowledge amounts to can be rather tricky, but in many cases it seems related to the experts' own experience and interpretation of certain nonclear-cut, possibly ambiguous, situations. For instance, this knowledge may involve practical experience of model behavior, interpreting ambiguous data and the relative relevance of feedback processes, drawing connections and building links between disciplines, among other things. Many of these aspects are not always "explicit in the formal literature".[14]

In particular, in the context of climate and Earth system tipping points, expert judgment can typically draw fruitful connections between precise mathematical considerations about low-dimensional systems in dynamical systems theory and possible concrete physical features of the extremely high-dimensional complex systems under interest. Indeed, if abstract results from dynamical systems theory may not directly apply to high-dimensional complex systems such as the climate or Earth systems, they can however inform expert judgment by providing a qualitative perspective "exploring mere possibilities of tipping points and devising methods to analyze and categorize them" (Bathiany et al., 2016, p. 22, where this "top-down" approach is contrasted with a standard "bottom-up strategy" based on "modeling certain processes with as much realism as possible"; Bathiany et al., 2016 convincingly argue that the two perspectives are best seen as complementary).

As an example, different kinds of tipping mechanisms have been identified in nonautonomous dynamical systems (Ashwin et al., 2017), suggesting in particular the possibility of a critical transition while no parameter threshold (or bifurcation) is crossed (rate-induced or R-tipping). Among other things, such mathematical considerations can inform experts about the limitations of focusing only on alternative equilibria and bifurcations (Bathiany et al., 2016; Ghil & Lucarini, 2020). It is interesting to note that these considerations can also inform modeling investigations (via expert judgment): partly motivating their work with the very possibility of rate-induced tipping, Lohmann and Ditlevsen (2021) recently show the existence of "a rate-induced collapse of the AMOC" in a global ocean model with time-dependent freshwater forcing,[15] hence further suggesting "that the existence of alternative and undesired stable states [of the AMOC] may be already a risk even if the tipping point is relatively far away".[16] These results have prompted the IPCC in the AR6 report to reassess the abrupt collapse of the AMOC before 2100 from "*very unlikely*" to "*medium confidence* that it will not occur", despite the fact that "[n]one of the CMIP6 models features an abrupt AMOC collapse in the 21st century" (IPCC, 2021, §9.2.3.1).

3.3 | The relationship between expert judgment and modeling

In general, the very fact that expert judgment can inform modeling is rather obvious and uncontroversial. What is interesting to highlight, though, is that the relationship between modeling and expert judgment goes both ways (Thompson, 2022). Indeed, on the one hand, as we have just mentioned, expert judgment plays a role at almost every stage of model construction and model assessment (e.g., in choices about structural features of the model, in the parametrization and tuning procedures, in the uncertainty assessment). But, on the other hand, the models also nourish expert judgment in many ways (e.g., climate model simulations may provide understanding, despite some challenges, see Parker, 2014b).

Thompson (2022) raises concerns about this epistemic loop, which may potentially lead to a selection bias––which actually does affect tipping points to a certain extent, as we mentioned in Sections 1 and 2.1––and overconfidence (thus underestimating uncertainty). Theoretical (e.g., physical, "process-based") arguments, and in particular mathematical considerations of the kind mentioned above (e.g., from dynamical systems theory), may help to open up this epistemic loop. However, how to strike an epistemically virtuous balance between modeling and expert judgment remains a challenge––partly to be addressed on a case-by-case basis (the issue also strongly depends on the purpose under consideration).

For the time being, the actual practice in climate science tends to be "tilted" towards modeling: even under high (or deep) uncertainties, model outputs tend to be epistemically more valued––especially when it comes to decision-making––than expert judgment, which in general does not only rely on modeling considerations. For instance, the epistemic imbalance between model outputs and expert judgment has been recently highlighted in the context of regional climate change information and related uncertainty assessment, and strategies are being developed to overcome it (see, e.g., Thompson et al., 2016, Shepherd, 2019, Shepherd & Lloyd, 2021). Indeed, such an imbalance may not always be epistemically warranted, especially in conditions where the reliability/adequacy of climate models cannot be quantitatively assessed (e.g., because representative observational data are lacking), as well as when high or deep uncertainties are involved––such as in the context of tipping points.

3.4 | Expert judgment as a scientific output

Even if it is not explicitly stated, expert judgment about climate and Earth system tipping points is actually often used as a genuine scientific output, complementary to––but not independent of––model outputs. In this sense, expert judgment possesses a central and somewhat specific status in the context of tipping points, one that is linked to the presence of high or deep uncertainties, but that does not "reduce" to assessing uncertainties, as in many instances of expert judgment in climate science (see Section 2.1).

For instance, in this perspective, the very identification and characterization of tipping elements in the Earth system through expert elicitation procedures (see Sections 2.2 and 3.2) are understood as genuine scientific outputs on their own. Similarly, expert-based investigations into interactions between tipping elements aim to provide new (qualitative) insights, beyond the capacities of current state-of-the-art Earth system models. As a concrete recent example, Wunderling et al. (2021) qualitatively investigate tipping cascades in a set of four tipping elements using a conceptual model consisting of a "stylized" nonlinear differential equation involving a (cusp) bifurcation and a (linear) coupling term. Both the bifurcation dynamics and the coupling term directly result from expert judgment: the main coupling parameter (the interaction link strength) is based on the expert elicitation in Kriegler et al. (2009), and the choice of the bifurcation dynamics relies on theoretical considerations (e.g., the salt-advection feedback in the AMOC case),[17] on certain modeling experiments, as well as on paleoclimate data (e.g., Dansgaard-Oeschger and Heinrich events in the AMOC case). Wunderling et al. (2021)'s investigations are not intended to "make predictions of any kind", but rather provide an assessment of "the qualitative role of known interactions of some of the most critical components of the climate system" (614)––an assessment that can "lay the foundations and possibly guide towards a more detailed analysis with more complex models or data-based approach" (602). Such a qualitative, expert-based study is therefore meant to be complementary to further modeling investigations, including in view of addressing possible policy implications (e.g., Cai et al., 2016 use Kriegler et al.'s expert assessment of interaction between tipping element to run their integrated assessment model).

3.5 | Epistemic pitfalls

Because of the context of high (or deep) uncertainties within which expert judgments about climate tipping points are made––and which, in many ways, constitutes (part of) their raison d'être in the first place––the epistemic foundations of these expert judgments require a very careful evaluation. Indeed, the main expert-based claims about tipping points in the literature do not have all the same epistemic status. On the one hand, expert-based claims resulting from a structured elicitation protocol such as in Kriegler et al. (2009) (see Section 2.2) can expect a rather robust epistemic standing; indeed, the assessment in Wunderling et al. (2021), made more than 10 years later, shows that "[o]verall, the additional literature supports and refines the results" (606) from the expert elicitation in Kriegler et al. (2009). On the other hand, expert-based claims about (for instance) a global tipping point for the entire Earth system ("planetary threshold") irreversibly leading to a "Hothouse Earth" (Steffen et al., 2018), result from the investigations of a rather small group of scientists and thus may possess a more speculative epistemic status. Note that the latter comment does not amount to denying the relevance of such more speculative investigations for certain purposes, such as exploring very high impact ("worse-case") scenarios or climate change communication (see Lenton et al., 2019).[18]

Structured elicitation protocols may strengthen the epistemic status of expert-based claims about climate tipping points, but given the high uncertainties involved, they are neither sufficient nor necessary for such claims to be epistemically warranted. In the end, the epistemic evaluation of expert-based claims should of course be made on a case-by-case basis.[19] However, we want to highlight two elements that require careful attention in this context.

First, there is an intuitive sense in which the epistemic status of an expert-based claim about climate and Earth system tipping points should be indexed in time: indeed, a well-grounded expert judgment made at some time t may become less warranted 10 years later in the light of new evidence. So, expert judgment needs regular updating. This is explicitly acknowledged in Kriegler et al. (2009, 5045), which is unsurprising given the Bayesian framework they assume (see Section 2.2): "It should be noted that expert beliefs are tied to the time of elicitation, and may be updated in light of new information." However, as recently noted in Wunderling et al. (2021), an updated expert elicitation has not been carried out more than 10 years later, despite the new knowledge about climate and Earth system tipping points that has emerged since then (similarly, Armstrong McKay et al., 2022 write that "an updated expert elicitation [building on Kriegler et al., 2009] is overdue").[20]

Second, as briefly mentioned above (in Sections 2.2 and 3.1), it is quite largely acknowledged that nonepistemic values play some nonnegligible role in climate science; now, given the subjective aspects of expert judgment, nonepistemic values may also clearly play an important role in this context. To a certain extent, this role can be mitigated by the structured elicitation process; as an example, the fact that experts from different regions of the world may have different nonepistemic values and priorities can be (partly) mitigated by transparently forming groups of experts with a high geographical diversity (Lenton et al., 2008 list the countries of affiliation of the experts participating in elicitation process; nine countries are represented––all from the global North though). However, and in the light of the work in philosophy of science about the entanglement of nonepistemic values with the actual practice of climate science (as discussed in Section 2.2), one needs to be aware of the (potentially irreducible) role of these values in the climate context––and for expert-based claims about climate tipping points in particular. This awareness of values is a crucial first step to avoid biases, but then how to manage these values remains an open issue and still needs to be debated; in particular, such a debate could gain from involving both the climate science and the humanities (Pulkkinen et al., 2022). Of course, this issue is not specific to expert judgment about climate tipping points, but it does resonate in a particular way in this context, especially given the high uncertainties and the potential drastic impacts that are involved.

The issue of nonepistemic values becomes even more pressing within the framework of the recent developments in Earth system science that ambition to include not only all the relevant climatic and biogeochemical processes (in the atmosphere, ocean, land, cryosphere and biosphere components), but also all the relevant aspects of the human societies themselves (in the so-called "Anthroposphere" component), as well as interactions between these components (Donges et al., 2021). But the way to represent and model the human and social dimensions may of course be highly dependent on certain nonepistemic (e.g., socioeconomic and political) values. A paradigmatic example is given by the influential Bretherton diagram depicting in a very schematic way the interactions between various subsystems of the Earth system (Steffen et al., 2020, figure 2; see figure 3 for an update version of the diagram), and where the "Human activities" are represented as a mere box interacting with the other natural subsystems. As largely discussed in the social sciences, this undifferentiated representation of human society carries certain (e.g., "techno-managerial") values at the expense of other ones (e.g., about social justice; see for instance the discussion in Lövbrand et al., 2015 and in Bonneuil & Fressoz, 2016, ch. 4). Furthermore, in this context, there have been recent calls for inducing "positive" social tipping points (Lenton, 2020), which are typically identified through expert elicitation processes (Otto et al., 2020; Winkelmann et al., 2020). Similarly, the issue of the values that are involved in these approaches to "climate action" needs to be carefully considered.

4 | CONCLUSION

As the field currently stands, expert judgment plays a large role in understanding climate and Earth system tipping points. In this paper, we have reviewed this role and its nature, highlighting a number of methodological and epistemic elements. One of the main upshots of our discussion is that expert elicitation is not only used for the quantification of uncertainty in this context, but also for the very identification and characterization of tipping points and their interactions, making expert judgment in itself a genuine scientific output. We have seen that this status, and more generally the central role of expert judgment in this domain, raises several epistemic issues that require careful attention. For instance, the relationship between expert judgment and modeling has to be carefully assessed in order to avoid biases. Similarly, the (nonepistemic) values that are involved in expert judgment need to be explicitly acknowledged, openly debated and appropriately dealt with (e.g., using adequate structured elicitation protocols)––and even more so when it comes to expert judgment about tipping points involving social processes (as within the encompassing perspective of Earth system science).

Given the persisting high (deep) uncertainty in this context, expert judgment will continue in the foreseeable future to be an important and necessary tool for making claims about climate and Earth system tipping points and their interactions, in particular when it comes to assessing their potential impact. In this perspective, it may well be relevant to explore several different ways to articulate expert judgment, for instance through physical storylines for tipping points (indeed, the last IPCC report AR6 acknowledges the relevance of storylines for assessing "low-likelihood high impact" events, see IPCC, 2021, §1.4.4).

AUTHOR CONTRIBUTIONS

Vincent Lam: Conceptualization (equal); formal analysis (equal); funding acquisition (lead); investigation (equal); methodology (equal); project administration (lead); resources (equal); supervision (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Mason Majszak:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal); resources (equal); software (equal); supervision (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST

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DATA AVAILABILITY STATEMENT

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ENDNOTES

[1] There have been many proposed principles in social epistemology for framing this discussion; Martini has provided a synthesis and evaluation of the literature (Martini, 2014, 2015, 2020).

[2] See Goldman (2001, 2018) and Croce (2018) for more on these ongoing debates.

[3] See Martini (2014, 2015, 2020) for an overview and evaluation of these principles of expertise from a social epistemology viewpoint.

[4] This can be in tension with the fact that these subjective elements actually play an important role for expert judgment in climate science (Majszak & Jebeile, 2022).

[5] For more on the IPCC's terms for communicating uncertainty see Mastrandrea and Mach (2011), Adler and Hadorn (2014), and IPCC (2021, ch. 1).

[6] The latest IPCC report AR6 explicitly acknowledges the relevance of moving beyond the standard uncertainty framework in situations involving highly uncertain or potentially surprising climate outcomes, for instance using physical storylines (IPCC, 2021, §1.4.4; Shepherd et al., 2018); these latter also centrally involve expert judgment.

[7] For an overview and evaluation of the differences between these protocols see O'Hagan (2019).

[8] For a full description of the methodology used in this structured elicitation protocol, see Appendix 3 of Lenton et al. (2008) and Appendix 1 of Kriegler et al. (2009).

[9] Linear and logarithmic opinion pooling are axiom-based aggregation rules, meaning they are to maintain certain properties when aggregating probability judgments (Clemen & Winkler, 1999). However, it should be noted that no pooling rule can maintain all desired properties (Kriegler et al., 2009, Appendix 1). Nau's pooling rule conversely is oriented for imprecise event probabilities, focusing on lower and upper bounded probabilities (Nau, 2002). For a full review on the different pooling methods see Clemen and Winkler (1999) and Nau (2002).

[10] For instance, within the framework of nonautonomous dynamical systems, Ashwin et al. (2017, p. 2186) note that "even in idealized cases, it is a challenge to come up with a mathematically rigorous and testable definition of

'tipping point'"; there are indeed many inequivalent understandings of the notion of tipping point in the climate science literature (see Lam, 2022 for a recent general overview of the epistemic and methodological issues related to the definition of tipping points). Note that specific and detailed definitions for particular events involving tipping point (e.g., "reorganization/collapse of the Atlantic meridional overturning circulation") were used in the elicitation process discussed in Section 2 (see the Appendix 1 and the table S1 of Kriegler et al., 2009).

[11] The definition adopted in the latest IPCC report AR6 is somewhat broader (and less precise), but also makes reference to Lenton et al. (2008): "a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly" (IPCC, 2021, §1.4.4.3).

[12] Lenton et al. (2008) define a "political time horizon" T_P within which decisions can influence whether a tipping point is reached or not, as well as an "ethical time horizon" T_E beyond which future tipping behavior may not be policy relevant because too far away; the suggested values are 100 and 1000 years for T_P and T_E respectively.

[13] The role of nonepistemic (e.g., social, ethical, economic, political, …) values in climate science and climate modeling has recently been acknowledged by some in the climate science community (IPCC, 2021, §1.2.3; see also Pulkkinen et al., 2022); this topic has been quite largely discussed in the philosophy of (climate) science in the last decade or so (Betz, 2013; Biddle & Winsberg, 2009; Frisch, 2020; Intemann, 2015; Jebeile & Crucifix, 2021; Parker, 2014a; Parker & Winsberg, 2018; Winsberg, 2012). How the debate about values and value management should be implemented raise many issues––political issues, among others––that still need to be addressed (see Lusk, 2020, 2021 for first steps).

[14] This "holistic picture" of expert judgment actually relates to several epistemological themes linked to evidence amalgamation such as the variety of evidence thesis and robustness analysis (see the recent special issue Fletcher et al., 2019 on "Evidence Amalgamation in the Sciences").

[15] Of course, there are several lines of evidence suggesting the rate-dependency of the AMOC collapse, including from earlier simple modeling studies (Stocker & Schmittner, 1997).

[16] These features "point to fundamental limitations in climate predictability," according to Lohmann and Ditlevsen (2021)––see however Ritchie and Sieber (2016); similarly, the mechanism of noise-induced tipping, where the tipping behavior is induced by stochastic fluctuations, seems especially challenging for "early warning signals" or indicators (Ditlevsen & Johnsen, 2010).

[17] As we have seen above (Section 3.2), it has been argued that, beyond the standard bifurcation structure, the AMOC may actually involve a rate-dependent tipping point (Lohmann & Ditlevsen, 2021).

[18] The extent to which the notion of tipping point––and in particular global tipping point––is relevant for climate change communication is debated (see the debate between Michel Crucifix and James Annan in Hulme, 2020, ch. 2; about the tipping point trend in climate change communication, see Russill & Nyssa, 2009).

[19] This evaluation involves assessing the methods to generate and aggregate expert judgments (Section 2.2), as well as the different dimensions constituting expert judgment, such as theoretical understanding, observational and paleoclimate data, model outputs, … (Section 3.2); in this perspective, it could be useful to articulate a framework to assess the quality of expert-based claims about climate and Earth system tipping points, similarly to what has been recently suggested for regional climate information (Baldissera Pacchetti et al., 2021).

[20] This updating can take different forms; there is actually a proposal 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).

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