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Doing better rather than promising more: A basic principle applicable to both climate modelling and climate policies

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Abstract

A growing number of scientists are expressing concerns about the inadequacy of climate change policies. Fewer are questionning the dominant climate modelling paradigm and the IPCC's success to prevent humanity from venturing unprepared into hitherto unknown territories. However, in view of an urgent need to provide readily available data on constraining uncertainty in local and regional climate change impacts in the next few years, there is a debate on the most suitable path to inform both mitigation and adaptation strategies. Examples are given how both common statistical methods and emerging technologies can be readily used to exploit the wealth of existing knowledge to drive adaptation policy. Parsimonious and equitable approaches on constraining uncertainty are promoted that combine various lines of evidence, including model diversity, large ensembles, storylines, and novel statistical methods applied on well-calibrated, global and regional, Earth System simulations, to deliver more reliable climate information. As examplified by the Paris agreement on desirable global warming targets, it is argued that the display of unrealistic ambitions may not be the best way for climate modellers to accomplish their long-term objectives, especially given the growing consensus on climate emergency and the allocated short time for the knowledge to be delivered and applied.

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1. Introduction: Forty-five years of half-baked success

In February 1979, the World Meteorological Organization (WMO) organized the first World Climate Conference in Geneva. Hundreds of experts from different fields agreed about the urgent need to improve scientific knowledge of climate and to use this knowledge to "*predict and prevent possible human-induced climate change that could affect the well-being of humanity*". The World Climate Research Program (WCRP) was then established to achieve this objective and to coordinate related research activities. Forty-five years later, this program has gained international recognition and taken on many challenges. Yet, both the prediction and prevention objectives have been so far a half-baked success. In the light of current ambitions on climate action falling short of what is required to limit global warming [1] and of the increasing cost of climate change impacts [2], both scientists and decision makers must question the effectiveness of their methods to best inform their fellow citizens of the risks incurred according to the socio-economic scenarios they may choose (or suffer) to face (or deny) this civilizational challenge.

In December 2015, the Paris Agreement was adopted by 196 parties at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change. Its long-term objective was to "*substantially reduce global emissions to hold global temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels*". It implied that global emissions of greenhouse gases (GHG) should be cut by roughly 50% by 2030 before reaching net zero by the middle of the century, as a result of an increasing aggregate of each country's nationally determined contributions. Implementation gaps in these pledges may however lead to a significant and persistent overshoot of global mean temperature, with uncertain consequences at the regional scale.

In December 2023, the COP28 was marked by the first "*global stocktake*" of the world's efforts to fullfil the Paris Agreement. Once more, it closed with a call on governments to speed up the transition away from fossil fuels to renewable energies, and another call on scientists to further expand their knowledge on climate change. After a workshop on the future of climate modelling [3], specific recommendations were made regarding the priority research areas for the next few years preceding the release of the 7th Assessment Report (AR7) of the Intergovernmental Panel on Climate Change (IPCC). Yet, the comprehensive content of this synthesis highlights the difficulty to agree on the most urgent and tractable priorities.

The present opinion paper points to what is argued is a common flaw in climate policy and climate modelling: the display of unrealistic ambitions in view of the proposed solutions and available resources. It is first argued (Section 2) that the failure of the Paris Agreement was predictable and that this (too?) ambitious mitigation target has eventually contributed to an overall feeling of powerlessness. It is then suggested (Section 3) that broken promises are not the prerogative of policy makers, as illustrated by the symptomatic case of km-scale climate modelling. Alternative priorities for climate modelling are then suggested (Section 4) and, ultimately, placed in a broader context to improve the dialogue between scientists and policy makers (Section 5). Without calling for a step back as radical as that advocated by Lewis Mumford [4] in his critique of the so-called "*authoritarian technique*", returning to a point where we can have a choice, adapt and make plans partly different from technical solutions and computing sciences appears to be a necessity to restore not only their creativity but also their appeal to climate sciences and climate policies.

2. The loaded IPCC's dice

The fifth Assessment Report of IPCC was instrumental in building the political momentum that led to the Paris Agreement [5]. Yet, the agreement was signed with only limited knowledge about the implications for both adaptation and mitigation policies. Parties thus invited the IPCC to assess the impacts of global warming of 1.5˚C versus 2˚C above pre-industrial levels and the feasibility of the related emissions pathways. This SR1.5 special report [6] led to the principle of climate emergency: "*every bit of warming matters*, *every year matters*, *every choice matters*". Yet, jumping to the conclusion that limiting warming to 1.5˚C is not only desirable but also "*possible within the laws of chemistry and physics*" may suggest that the IPCC is still biased towards physical rather than human sciences.

2.1 The Paris agreement: Destined to succeed or doomed to fail?

The Paris Agreement is generally considered as a milestone in international climate policy. Climate change is not only seen as a major environmental problem, but also as a challenge to fundamentally transform global societies. Since the agreement was adopted, there seems however to be a persistent lag between the peer-reviewed literature and the overall public perception about our collective ability to limit global warming at a safe level. Despite the SR1.5 warning about the "*unprecedented scale of the challenge*" required to keep warming to 1.5˚C, few peer-reviewed studies have been lucid enough to predict our apparent failure to meet this target (at least without a significant and lasting overshoot in global mean temperature).

At the individual level, trust and risk perceptions are key prerequisites to the support of mitigation policies. Cross-national differences in climate change attitudes however highlight the possibility of a "*social trap*" whereby a lack of trust blunts the effect of risk perceptions on public willingness to tackle climate change [7]. Most governments are struggling in finding actionable trade-offs between supply and demand policies. A comprehensive pricing of carbon emissions, one of the economically most efficient demand policy, often face strong political resistance. Public support is sensitive to the efficacy, but also to the progressivity and equity of the proposed solutions [8]. Trust is more difficult to build than to undermine and any misstep in the design or implementation of mitigation actions may cause an irreversible delay in achieving the long-term objectives.

Arguably, the failure of the Paris Agreement was predictable at the time it was ratified [9, 10]. The hiatus between the expert and public discourse on its feasibility has partly arised from the persisting under-representation of some fields or dissident views of human sciences, both in the IPCC and the media treatment of climate change. The SR1.5 has not paid enough attention to the social acceptability of the drastic mitigation policies required for limiting global warming well below 2˚C [6]. It has also ignored the long-running political debate about the relevance of the sustainable development concept [11] and underestimated well-known limitations of the desired decoupling between economic growth and GHG emissions [12]. A lack of critical view towards the proposed mitigation solutions may also have biased the debate on the question of political voluntarism rather than individual responsability.

As in the case of the health crisis linked to the Covid pandemic, many climate scientists also seem to ignore the socio-economic aspects of climate change. Most policymakers continue to assume that damage costs are manageable while decarbonization is much more expensive. Both assumptions are increasingly questionable: the cost of green energy has dropped rapidly, while damages from climate change are increasing faster than projected [2]. The latter issue is already a major concern for a growing number of countries who are already bearing the economic and non-economic burden of climate change. It also participates to the failure of climate negotiations around the pressing question of who will pay for "*loss and damage*". The fact that they are still treated as an option rather than a key component of the Paris Agreement has become a major matter of concerns for the Global South and a divisive issue among major greenhouse gas emitters.

Many of these major obstacles could have been anticipated. How did it then happen that so many Parties ratified the Paris Agreement? Governments have been facing a growing pressure from the scientific community, the media, and a growing fraction of their population to raise their ambition in tackling climate change. Although crucial for moving forward, such a social pressure may also have unintended negative consequences [13]. It can for instance undermine the Paris Agreement's desired flexibility, which allows Parties to design their Nationally Determined Contributions (NDCs) according to domestic conditions and capabilities. It may also result in widespread noncompliance by inciting pledges that the countries concerned prove unwilling or unable to fulfill.

The geophysical feasibility of the Paris Agreement has given no excuse for governements not to succeed in keeping global warming well below 2˚C and, ultimately, has eroded the public trust in their capacity to tackle the problem. Conversely, the WCRP and IPCC agendas have been increasingly influenced by policymakers, including in the exploration of high-mitigation techno-solutionist scenarios that are needed to maintain the so-called "*green growth*" and a high level of employement, but are unlikely to achieve in due time the expected decoupling between GHG emissions and economic development. This flawed dialogue between scientists and policymakers is all the more worrying that no one really knows what a net-zero emission global economy may look like by the mid-century [14]. Meanwhile, the apparent powerlessness of governments has created a climate of anxiety and discontent conducive to the rise of populism [15]. The emergency framing of climate change may also have contributed to this political situation: populism tends to be something presenting itself as a politics of volition rather than necessity [16].

2.2 Too little or too much ambition?

Climate scientists increasingly criticize the lack of ambition of the current mitigation policies, regardless of the other socio-economic and geopolitical dimensions of the problem. Yet, some of them had to organize another model intercomparison project (MIP) [17] to realize that even an episodic collapse of the global economy due to the Covid pandemic is far from enough to have a significant effect on the global mean surface air temperature (GSAT). The induced global cooling was assessed to be around 0.01 ± 0.005˚C by 2030 [18], while the economic burden was tremendeous for many countries especially in the Global South where millions of people returned to extreme poverty [19]. In this context, the comprehensive name of the SR1.5 IPCC report [6] (*an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways*, *in the context of strengthening the global response to the threat of climate change*, *sustainable development*, *and efforts to eradicate poverty*) sounds like a challenge that cannot be addressed within a few years, but rather needs a long-term planning incompatible with the ambition of the Paris Agreement.

Beyond the question of temporality, the objective of the Paris agreement is clearly disproportionate to the method used [9, 20]. Even if all the pledges embedded in the NDCs were fully implemented, the increase in GSAT will predictably be far above +2.0˚C [21]. There are thus many reasons to doubt whether the agreement could succeed. The most quoted weakness is the lack of legally binding emission targets although such a flexibility was probably essential to the participation of many countries. Another key issue is the persistent discrepancy between the international climate and trade liberalization objectives. As long as the World Trade Organization (WTO) is not under the United Nations' umbrella and that each country's prosperity is measured by the Growth Domestic Product, moving away from fossil fuel energies is bound to be long and difficult.

There is also a persistent lag between the intended NDCs and the limited capacity of goverments to deliver on their promises. This implementation gap has been heavily criticized, including by the Secretary-General of the United Nations. Yet, what is the key explanation: not enough action or too much ambition in a context of growing economic inequalities, the failure of democracies to protect the most vulnerable, and the rise of populism? The answer may lie not only in the resilience of societies to a warming of 2˚C rather than 1.5˚C, but also in the inability of democracies to withstand such an abrupt transition [22]. To make the Paris Agreement a plausible future, citizens should not accept only radical behavior change, but also have altruism across borders and for future generations.

The willingness of governments to address the climate emergency encounters strong resistance from the population as soon as people realize that the required mitigation efforts pose them an existential threat. The French "*Yellow Vests*" opposition to carbon taxes provides a first example of this debate. Many of them insisted that they support taking action to curb climate change, but protested against the unequal distribution of wealth before establishing a "*universal*" tax that will target disadvantaged socioeconomic classes. Carbon taxes can be an effective mitigation solution only if they do not inherently disadvantage and harm lower-classes and developing nations. Otherwise, the near-term benefits of adaptation may still exceed the long-term expectations of mitigation efforts for the most vulnerable communities. The only way out of this dilemma seems to be an ethic of climate justice and a guarantee that everyone contributes to mitigation according to the principle "*of common but differentiated responsibilities and respective capabilities*" [23].

The climate policy of the United States provides another enlightening example of the precarious balance between near and long-term benefits. Two short years after COP21, Donald Trump announced in his inaugural address that the US will withdraw from the Paris Agreement, under which the country would have voluntarily "*harmed American workers and disadvantaged its economy*" [24]. Exactly four years later, Joe Biden signed the paperwork to rejoin the Paris Agreement and declared that he wanted to "*raise the ambition of the US climate targets*". Beyond words, he pushed through an unprecedented budget to reduce energy costs, combat the climate crisis, and advance environmental justice. Yet, the US has achieved only one third of its 2030 emissions reduction target and President Biden has recently approved a controversial oil drilling project in Alaska despite his 2020 vow not to approve any new oil and gas leases on public lands.

So far, the performance of democracies on climate actions has been mixed [25, 26] and the emergency framing of climate change has not improved the situation. This can be explained by at least two reasons which countradict both what climate change deniers and the most radical environmentalists often claim. On the political side, climate change is not another "crisis" but the profound, widespread and partly irreversible consequence of more than two centuries of economic development, at an unprecedented rate and with huge short-term benefits for a limited fraction of the world population. It will thus take more than a few decades to establish the balance of power and the global policies that will allow the international community to agree on the mutual responsabilities and solve the problem, Especially, if we want to avoid quick and dirty geo-engineering techniques that most climate scientists still consider a cure worse than the disease while others have already called upon the United Nations to make an immediate decision for an International Non-Use Agreement [27].

On the scientific side, every ton of emitted CO_2 and additional increment in global mean temperature matters. Yet, there is no consensus regarding an abrupt shift in the probability of triggering tipping points by crossing a unique and critical GWL [28]. Unfortunately, the SR1.5 report seems to have reified the 1.5˚C target as the absolute definition of the Earth system sustainability, leading to the overall public opinion that it will be soon – if it is not already – too late to avoid the catastrophe [29]. In such an emergency situation, maintaining democracy may become incompatible with guaranteeing safety. A salient example is again the Covid pandemic, during which severe limitations on free movement have become legitimate strategies of European authorities. If policymakers want to avoid choosing between an authoritarian power and a run-away climate change, they must act to ensure greater population's adherence to public policies [30]. Rather than fueling the growing anxiety and anger of the population, the role of climate scientists could be to pave the way towards a transformation of our societies, both in the proposed mitigation actions and their research practices.

3. A paradigm-shifting pandemic

The Paris Agreement implies fundamental changes to how society functions, including changes to underlying values, ideologies, social structures, political and economic systems

[21]. More than ten years ago, Jim Skea, the current Chair of IPCC, edited a special issue of Climate Policy entitled "*Climate policies in a changing world context*: *is a paradigm shift needed*?" [31]. The response was that climate policies should be the pillar of a "*green growth*", with a view to securing a sustainable development. Yet, such a "*paradigm shift*" may be also considered as the continuation of an outdated economic system [32]. Likewise, the latest WCRP report on the future of climate modelling [33] envisions that climate modeling will undergo a "*paradigm shift*" between now and 2030, but struggles to convince the whole community about the most suitable pathways to reach such an ambitious objective. In this section, I claim that the current funding and functioning of climate research have led many scientists to be overconfident about their ability to predict climate change and to deliver policy-relevant key messages.

3.1 Broken promises are not the prerogative of policymakers

Since the establishment of the IPCC in 1988, climate change assessments have been dominated by a strong reliance on GCMs [34]. In line with this "*climate modelling paradigm*", multi-model ensembles of increasing complexity, resolution and size have been applied to assess three additive sources of uncertainty [35–37]. First, there is uncertainty about future GHG emissions and as a result about future GHG concentration pathways [38]. Second, there is a lack of knowledge about the overall Earth system and thus model uncertainties which can be assessed by comparing multiple GCMs from different institutes within the Coupled Model Intercomparison Project (CMIP). Third, internal climate variability remains a significant source of uncertainty, especially for near-term projections and/or low-likelihood extreme events, and has given rise to decadal forecasting with the growing development of global ocean data assimilation systems and high-performance computing resources.

Regarding the latter point, the Decadal Climate Prediction Project [39] may provide an edifying illustration of the unfulfilled promises of climate modellers. Decadal predictions differ from near-term climate projections due to the fact that they are driven by initialized oceanic conditions on top of prescribed radiative forcings (including unpredictable volcanic eruptions in retrospective forecast systems). While WCRP recognized that there is less skill in predicting precipitation and other variables compared to temperature at multi-annual timescales (https://www.wcrp-climate.org/dcp-overview), progress was expected to be made rapidly with the emergence of high-resolution climate models and increasing computing resources [40]. Yet, this so-called "*promising opportunity*" has failed to deliver substantial progress so far, including in the AR6 [41], and has apparently disappeared from the latest science priorities [33, 42]. Moreover, several studies suggest that the signal-to-noise ratio can be underestimated in climate models, thus requiring very large ensembles to extract the predictable signal [43], or that what was so far considered as internal variability could be, to a large extent, a response to the anthropogenic radiative forcing [44].

Looking at the outcomes of two other MIPs (which I co-designed) further supports that ambition and implementation gaps are not the prerogative of policymakers. The Cloud-Feedback Model Inter-comparison Project (CFMIP) is primarily aimed to inform future assessments of cloud feedbacks but has also evolved toward a better under-standing of regional changes in atmospheric circulation and precipitation [45]. Despite an impressive list of achievements, CFMIP did not really help global modelling centres to identify how they could improve their ESMs. While the early focus was on the tropical low-level cloud feedback, other potential reasons were unravelled behind the inter-model spread in climate sensitivity [46–48]. Moreover, many institutes that had commited to participate to optional atmosphere-only experiments eventually did not, thus limiting the scope and relevance of related analyses that aimed at a better understanding of modelling uncertainty [49].

The case of the Land Surface, Snow and Soil moisture Model Intercomparison Project (LS3MIP) is also illuminating [50]. The ultimate coupled component of the project (i.e., the assessment of land surface feedbacks attributed to soil moisture and snow in an integrated framework) has failed for both underestimated scientific and technical issues. The relevance of these feedbacks thus remains poorly understood despite their potential underestimation by most GCMs [51] and the long-standing debate on the contribution of land-atmosphere interactions to circulation changes, precipitation recycling, temperature extremes and the terrestrial carbon uptake in a warming climate [52–58].

From an IPCC perspective, the disproportionnate CMIP ambition of global modelling centres led to a strong delay in the provision of the simulations. Even the final AR6 WGI draft was mostly fueled by CMIP5 studies (around 80% of the quoted CMIP studies) and/or preliminary rather than in-depth CMIP6 intercomparisons. Several AR6 Lead Authors have conducted multi-model analyses at the same time they were in charge of assessing the available literature and drafting their chapters. This issue has led some scientists to advocate for a disconnection between CMIP and IPCC assessments, in line with the Fast-track CMIP7 proposal (https://wcrp-cmip.org/cmip7/). Yet, the core of the proposed experiments seems to reduce the AR7 to the evaluation of historical and scenario experiments, while the IPCC WGI report is about "The physical Science Basis" of climate change and may also require more process-oriented MIPs.

Twenty-one model intercomparison projects (MIPs) were endorsed for CMIP6, which included 190 different experiments that produced around 40 PB of data [59]. This led to a carbon footprint exceeding 1600 tCO_{2e} just for the fourteen institutions involved in the Infrastructure for the European Network for Earth System Modelling (IS-ENES3 consortium). The amount of CMIP6 data made available on the Earth System Grid Federation (ESGF) archive was close to 8 PB, which is 5 times less than the total amount which was produced. The number of ESGF simulation years has increased by around a factor 3 from CMIP5 to CMIP6 due to the larger number of experiments and the larger ensembles produced. Yet, the amount of computing resources (core-hours) has increased much more (factor 25 to 50) due to the increasing model complexity and/or resolution. A further increase by an order of magnitude is typically expected for the CMIP7 exercise.

Despite its positive impacts on triggering model development and improving the workflow and post-processing of climate simulations, the operational burden of CMIP is thus increasingly criticized [60]. The definition of "core" or "deck" experiments has not prevented most global modelling centres to participate in many other optional MIPs, thus highlighting the richness of CMIP but also the difficulty to agree on priorities. Bjorn Stevens also considers that CMIP6 had "*less spark than CMIP5*" since innovation has gradually devolved into routine, thus eroding the cutting-edge endeavour of CMIP [60]. He emphasized that projections of both global warming and regional climate changes remain sensitive to "*minor treatments*" [61]. This led him and other colleagues to propose a leap change in climate modelling by running km-scale GCMs with an explicit simulation of deep convection [62]. Yet, this resource-intensive solution may not be the most straightforward and immediate solution to improve climate services.

3.2 A debate on suitable climate modelling pathways

Some renowned leading climate scientists have repeatedly proposed substantial changes to the practice of climate modelling over recent decades, though they generally disagree over what those changes should be [63–67]. Three parallel avenues were identified by Katzav and Parker (2015), with the common objective to surpass the current modelling strategy. The "*hierarchy* *approach*" argues for the development of hierarchies of models of lasting value, where the more complex models should relate in traceable ways to a simple model grounded in physical theory [63]. The "*pluralist approach*" calls for a greater diversity in modeling efforts, including more attention to structural diversity [65], parametric uncertainty or more empirical modelling approaches. Finally, the "*unified approach*" promotes an accelerated development of high-resolution models within a seamless prediction framework [67].

The establishment of a few multinational climate modelling centers that would pool human and computational resources in order to develop and deploy much higher resolution models is sometimes presented as a revolution [62], but considered as a risky gamble in the face of climate emergency and the persistent need to account for subgrid processes (e.g., shallow convection, cloud microphysics, land surface hydrology, photosynthesis, atmospheric chemistry), even at km scales. Moreover, and despite potential synergies, resource limitations make it unlikely that all three proposals can be pursued at the same time.

The overall resistance to the so-called "*Digital Twin*" strategy can be explained by the need for enhanced model diversity and the availability of improved model calibration methods [66–67]. An insufficient number of independent GCMs may lead to overestimate the total uncertainty in climate change impacts [68]. Many climates services rely on costly dynamical downscaling techniques and are thus in practice already based on a small number of global projections. The development of km-scale GCMs will not necessarily improve the situation. Sampling the internal climate variability by running large initial conditions ensembles remains a priority to project probability changes in weather extremes, still out of reach of most if not all km-scale GCMs. Moreover, the implementation of digital twins is not without danger. Ibrion et al. [69] recognize that the digital twin strategy presents many advantages, but they also emphasize that it "*is associated with risk and high uncertainties*", even in industrial sectors where digital twins are well established and at a higher advanced level than in climate modelling.

Chapter 10 of the AR6 WGI also warns that "*increasing resolution per se does not solve all performance limitations*" [70]. It may rather create useless tensions between the global and regional modelling communities. The latter still considers that "*it will take at least a decade, and probably longer, before multi-decadal convection-permitting GCM climate projections become feasible and widely performed*" [71]. Regional Climate Models (RCMs) thus remain essential to provide local and regional physically-consistent climate information. Bias adjustment has proven beneficial as an interface between climate projections and impact models, and is still needed when moving to higher resolution. Both global [72] and regional [73, 74] km-scale models still show significant biases in their simulation of precipitation extremes. Even at such a resolution, "*epistemic uncertainty remains large regarding frequency changes and the degree of intensification of the most extreme events*", which is partly due to the convective-permitting RCMs' diversity [74], while more idealized climate change experiments suggest a limited reliability of the added small-scale information in such regional projections, at least for precipitation [75].

Beyond model biases, the proponents of km-scale GCMs often fail to convince if not explain how they could deliver reliable statistics about rare or unprecedented extreme events that only few much coarser resolution CMIP6 models are so far able to provide. Although the performance and energy efficacy of supercomputers are still improving, they will not be sufficient to run large km-scale ensembles in a world where the electricity demand is exploding and low-carbon electricity currently represents only about 40% of the global electricity production. Counter what is often claimed, ultra-high resolution modelling does not represent a simplification since the removal of empirical parametrizations is canceled out by extra complexities in the development, running and post-processing of these models. This development will drain enormous resources that could otherwise be used to develop alternative strategies, including in Global South countries that still depend on others to assess their own exposure and vulnerability to climate change.

Enhanced horizontal resolution allows a better simulation of synoptic phenomena but does not necessarily translate into much more model consensus on their projected changes [74, 76, 77]. Even in present-day climate, it may still produce a wide range of outcomes [72, 74]. There is still often a confusion between resolution and reliability among decision makers. Impressive pictures of instantaneous model outputs indistinguishable from satellite imagery (e.g., Fig 1 in [62]) have never been a proof for the model capacity to capture the atmospheric response to enhanced CO2 levels. In contrast, [66] argue that traditional GCMs are not obsolete and that their calibration, far from being an atavistic weakness, is an essential element in the simulation and understanding of complex systems.

4. Priorities for climate modelling

How the state of knowledge of the changing climate can be improved remains a fierce matter of debate within the climate modelling community [62, 66]. Recently, the WCRP Earth System Modelling and Observations (ESMO) project was created to "*advance forecasts and projections of the Earth system on time scales ranging from a few weeks to several centuries*". It is a welcome initiative given the growing and widespread manifestation of climate change over recent decades, that indeed call for adapting data assimilation techniques from weather forecast to climate prediction applications. However it is still not clear which "*emerging modeling and observation technologies*" are supposed to make a real difference compared to previous strategies.

4.1 Looking for model diversity

Multi-model ensembles are considered to produce a set of independent estimates of climate change and have been very useful to gauge the likelihood of particular outcomes. Yet, climate modellers share observation datasets and model codes, thus challenging the independence hypothesis of their respective models [65, 78–80]. This complicates the analysis of multi-model ensembles but largely goes unnoticed with only few exceptions [37]. Despite growing efforts in model documentation, the climate modeling community may still need to improve its code-sharing practice to enable an objective assessment of model redundancy [65].

Climate impact studies and climate services are usually based on even lower numbers of RCMs or statistical downscaling techniques and there is no clear consensus on how to select the driving GCMs [81–84]. CMIP and the Coordinated Regional Downscaling Experiments (CORDEX) should thus be considered as "*ensembles of opportunity*" rather than custom-designed systems for societal applications. Long-standing errors remain in the simulation of key societally relevant climate parameters, such as seasonal or annual mean precipitation. Yet, their link with modelling uncertainty in future climate projections is far from being well understood. This calls for a large model diversity, possibly with the help of machine-learning, rather than the development of a few km-scale ESMs that did not prove to provide more consensus on future climate.

Likewise, statistical methods that are used to constrain CMIP and/or CORDEX projections could also benefit from a larger set of more independent models [37, 65, 85]. The "all models are wrong, but some are useful" paradigm is still valid, especially if one considers that wrong models can also be used to better understand climate feedbacks [85–87]. Once again, the search for the perfect GCM has long been recognized as a dead end by the dynamical downscaling community. The choice of the most suitable driving GCMs depends on both the targeted metrics and region [73–78]. Moreover, some GCMs that have been considered as outliers in terms of historical global warming can still be ranked among the best models in their representation of regional climate [81–84]. While WMO advocates for parallel and complementary climate modelling approaches [3], this may not be feasible given the limited manpower and fundings. Should climate scientists consider all approaches are equivalent or should they first turn to the most parsimonious and effective solutions? If the response is "*do them all*", why should the digital twin option monopolize most available resources?

This question has been the topic of a long standing debate [62, 66] which could be however revisited at a time when many voices call for more interdisciplinarity in climate change studies (https://10insightsclimate.science/), a concept that was first introduced by the French biologist Jean Piaget who stressed the importance of "*accomodation*" in the cognitive development. Accommodation is when a person alters existing schemas, or creates new ones, in response to new information that contradicts their existing understanding. This process enables flexibility and adaptation in learning. While km-scale ESMs may be considered as an accomodation to the lack of model consensus within CMIP, the turn to more immediate and parcimonious solutions (cf. next subsections) is a more adaptative approach in a context of climate emergency and limited clean energy resources.

Beyond the climate modelling community, the call for more interdisciplinarity is even stronger. Saltelli et al. [131] argue for instance that "*the projects of digital twins do not engage with critical and interpretative social sciences*" and contest the overall utility of the concept. They rather advocate for independent institutions to develop diverse models, prioritize communication with simple heuristic-based models, collect comprehensive data from various sources, and shift focus away from physics-centered variables to inform climate action. While such a strong position against km-scale models is also questionnable, the continuation of Section 4 will provide a few illustrations of possible ways to find a reasonable trade-off between heuristic-based and quasi-industrial, digital-twin, climate models.

4.2 Looking for an enhanced synergy between model developers and users

Despite the recognition that modeling uncertainty is often the primary source of spread in global climate projections, the gap between model developers and those who analyse their results within CMIP has not been reduced. On the one hand, understanding the key processes that drives one's model response is not necessarily the key to explain the inter-model spread. On the other hand, identifying emergent constraints across a multi-model ensemble does not lead to a systematic or rapid model improvement [80]. Even worse, the lack of model consensus within CMIP may lead to a form of discouragement among those working on traditional GCM improvement and open the door to more technical solutions such as digital twins as computing resources become available. Yet, these GCMs are not obsolete [66] and are still improving from one CMIP generation to the next [21].

"*The scientific community has repeatedly claimed that it will be able to provide more certainty in future in order to improve the rational basis for policy, but reveals ever more uncertainties as the timespan needed for reducing them, once proposed for the 1990s, now extends further into the next century*" [88] This late 20th century statement is still valid and may challenge climate modelers regarding their repeated ambitions to deliver more reliable climate projections. A synergy between model developers and users is still lacking and represents a potential obstacle to achieving this objective. The evaluation and calibration of ESMs is still mostly based on climatological biases and still does not pay enough attention to the various processes (not only snow and cloud feedbacks) that have been unravelled as significant drivers of the inter-model spread in climate projections. Reciprocally, even physically-based emergent constraints based on multi-model archives may lead to hypotheses that are not well supported by observations [68].

Two research avenues may then be promoted to enable a stronger synergy between model developers and users. The first one aims at a more systematic and objective exploration of parametric uncertainty than is possible when GCMs are directly used as the forward model [66, 67]. The preliminary methods (e.g., history matching) can be further improved with the help of machine-learning, expanded to other ESM components and focused on a more systematic consideration of climate sensitivity [81] but beyond the narrow definition of the global mean temperature response to a CO_2 doubling. Preliminary results point to structural model uncertainty and indicate that compensating errors and other defects inherent in the tuning of ESMs can be diagnosed with *ad hoc* statistical and machine-learning methods.

A second avenue involves a better understanding of the key mechanism underpinning the emergent relationships between present-day and future climates across a multi-model ensemble or successive generations of CMIP models [82, 83]. It could take the form of more detailed physical analysis of model outputs, demonstrating the mechanistic links whereby intermodel variation in X leads to corresponding intermodel variations in Y. This approach was undertaken for the snow-albedo feedback example [82] and proved to be robust across three generations of models [72, 83]. It is most straightforward for emergent constraints involving the same feedback process for both X and Y variables, the only difference being the time scale on which the process operates. Using more empirical relationships is more challenging and may involve the disentanglement of multiple and multi-scale processes. In doing so, it could benefit from the experience and skills of those in charge of developing the physical and biogeochemical schemes within ESMs.

4.3 Looking for an enhanced synergy between models and observations

Detection-attribution studies have already allowed a fruitful dialogue between observations and models, for instance by using historical simulations driven by individual (e.g., anthropogenic versus natural) radiative forcings to interpret observed changes in the recent instrumental records. Rather than applying repeatedly such methods to other regions and events, they could also be used to constrain the available projections. In doing so, both recent and future climates will be consistently scrutinized and modelling uncertainty are systematically narrowed by the most recent observations.

Climate change remains essentially a problem of extrapolation. Future climate has no perfect analogue in the past and has essentially remained a blind test without observational counterpart until recent decades. This has strong implications for both the evaluation and use of climate models. Complex climate models cannot be easily calibrated because they are simulating a never before experienced state of the system. Despite recent efforts [66, 67], the "*art*" of model tuning still lacks a comprehensive and consensual definition, and has often remained a hidden aspect of climate modelling. Many model developers are still reluctant to use the full instrumental temperature record for calibration [67]. This careful strategy is increasingly disputable since the human origin of the observed global warming is an established fact [21]. Yet, it remains an open debate how to best use the available observations to narrow the *prior* (model calibration) or *posterior* (Bayesian methods) distribution of CMIP outcomes.

In both cases, a stronger emphasis could be put on recent and updated observations, including more reliable precipitation datasets [85], more homogeneous atmospheric reanalyses [86], and longer multi-sensor satellite records [87]. The WCRP ESMO initiative (https://www.wcrp-esmo.org/) could be particularly helpful in setting such priorities. Yet, the ESMO activities are currently focused on three distinct objectives: i) advancing predictions and projections of the Earth system, ii) improving monitoring, understanding and attribution of climate system changes and impacts, and iii) advancing and harnessing emerging technologies.

Despite growing evidence [51], the monitoring of climate change is thus still not considered as a promising tool to advance climate predictions [51, 89] and machine learning is here mainly thought as a way to improve models or to post-process initialized decadal climate prediction, rather than to make the best use of the available projections [90]. In other words, although ESMO emphasizes the need of expertise integration, the most ambitious technological challenges are still put forward to the detriment of much simpler and more direct data assimilation techniques. Such recent developments coud however superseede less robust emergent statistical relationships [85, 91], even if they need further evaluation [92] and do not systematically lead to drastic reductions in modelling uncertainty [51, 93–96].

Not so surprisingly, the digital twin theory has also some support in the global observation community [97] which claims that remote sensing, as well as in situ and citizen observations, should be combined with high-resolution ESMs, artificial intelligence, information and communication technologies, and high-performance computing to monitor and simulate Earth processes with unprecedented spatiotemporal resolution. While they argue that advances in Earth observation (EO) satellite technology are pivotal for this purpose, their ambitious project seems far removed from current priorities that may rather consists in maintaining and improving observational capabilities in order to provide longer and more homogeneous (rather than higher resolution) instrumental records [98].

4.4 Moving from idealistic to contextualized choices

In a recent WMO white paper on the Future of Weather and Climate Forecasting, Brunet et al. [99] claim that urbanization and our changing global economy have also increased the need for accurate projections of climate change and improved predictions of disruptive and potentially beneficial weather events on km scales. They also argue that technological innovations are leading to a growing role of the private sector in the weather and climate enterprise. Their vision does not only rely on science, but is also driven by technological, economical and political considerations that may need further debate within and beyond the climate modelling community.

The WMO white paper calls for "*further improvements in accuracy and precision*, *higher spatial and temporal resolution*, *and better description of uncertainty which are needed for realizing the full potential of forecasts as enablers of a new level of weather-and climate-informed decision-making*" [99]. This apparent *statu quo* regarding the priorities hides growing tensions within the modelling community, and a possible lack of foresight in the face of the machine-learning irruption into climate sciences. These new methods can be used for a wide range of applications, from the calibration of dynamical systems to the representation of fine-scale processes in coarse resolution climate models [99, 100]. They can also emulate or constrain fine-scale details of climate projections [101], thus questionning the need of km-scale GCMs.

Jakob et al. [102] also emphasize the need to operationalize climate modelling, but recognize that several pathways are possible futures for this enterprise. They anticipate that the increase in the number of climate models will continue, but argue that "*exemplar groups that impose rigorous model development standards may not be advantaged over those that do not*". This kind of "prior judgement" is surprising given the recent list of too "hot models" and our growing ability to rank, weight or select the most suitable models at the regional scale. The authors also recognize that the establishment of operational climate modelling centres will lead to diminish the total number of models to "*about ten or so*". This implies that an increasing number of countries, not only in the Global South, will depend on others for designing their adaptation policy, something that may not be favoured as multilateral decisions become an exception rather than the rule [103].

Conversely, many climate scientists are still promoting an incremental approach and a continued improvement in our ability to simulate the Earth system response to, and the impacts of, climate change [42]. For this purpose, they suggest multiple non exclusive recommendations, from assessing the efficacy of negative CO_2 emission by using ESMs in CO_2-emission mode to the synchronization of regional downscaling and impact models with state-of-the-art global projections. They also call for a better understanding of changes in modes of variability and potential tipping points [104, 105]. The relative priorities of this ambitious to-do list may again deserve further discussion, as well as the growing role that observations or larger ensembles could play in this perpective.

Assessing the efficacy of negative CO_2 emission for climate cooling will need emission-driven ESMs [106] whose calibration partly based on the historical CO_2 concentrations may hovever represent a serious epistemic problem. Synchronizing regional downscaling and impact models with CMIP necessitates relatively coarse resolution GCMs (or much larger computing resources) and the completion of a representative GCM/RCM matrix of transient rather than time-slice climate simulations covering both the historical period and the whole 21st century. Even more than a large diversity of concentration scenarios, there is a need for better sampling the driving GCMs in order to span the full range of plausible climate change while avoiding the use of potential outliers.

Observations are increasingly used to challenge the multi-model ensemble mean as the most likely response to climate change. There are many cases where contradictory lines of evidence between observations and models should be reconciled as soon as possible [51, 93–96, 107–111]. Real-time sharing of historical instrumental records will strengthen the application of detection-attribution tools, which are also useful to quantify the historical responsibility of global and regional GHG emissions in changing the probability of policy-relevant extreme events [112]. Data rescue initiatives and longer observational time series are also needed to better understand internal climate variability and better isolate the forced component in the observed timeseries, including in the deep ocean or in continental water and carbon reservoirs.

5. Conclusion

Despite three decades of political efforts and a wealth of research on the causes and impacts of climate change, global GHG emissions have continued to rise and are much higher today than they were in 1990. Exploring this rise through multiple thematic lenses, Stoddard et al. [113] point to a common thread that emerges across the reviewed literature: "*the central role of power*, *manifest in many forms*, *from a dogmatic political-economic hegemony and influential vested interests to narrow techno-economic mindsets and ideologies of control*". Synthesizing the various impediments to mitigation may thus reveal how delivering on the commitments enshrined in the Paris Agreement requires an unprecedented transformation of our mentalities and ways of thinking.

The prediction that the Paris Agreement would fail at the time it was ratified was not pessimistic but, arguably, the safest way to get prepared (adaptation) and look for more feasible mitigation strategies. As a promise, net zero emission has been a great success [14], although relying on technological bets regarding our capacity to develop negative CO_2 emissions despite the adverse effect of a warming climate on the natural ocean and terrestrial carbo sinks. Such a promise has obscured our need to develop a new narrative where the focus could be as much on the rate of multi-variate climate changes than on absolute GWLs [114–116]. An abrupt overshoot of GSAT may be for instance neither feasible nor desirable given its fast and opposite impacts on both ecosystems and societies [117].

Besides the lack of solid scientific background of many decision-makers, the difficulty for many scientists to consider all cultural, economic, geographic, historical, social and political drivers of climate policies is also an issue. Yet, climate scientists cannot escape thinking about their own responsibility and simply comment on the inability of policy makers to curb the GHG emissions. The difficulty to provide accurate projections may have led to postpone urgent but unpopular decisions by governments. It has also partly undermined the long-standing ambition of CMIP to guide no-regret adaptation climate policies at the regional scale. The WCRP response to the climate modelling challenge should not be the substitution of an insufficient number of truly independent ESMs by an even lower number of km-scale models. On the contrary, this is the GCMs' structural diversity which has so far ensured the consistency and continuity of the successive IPCC assessments.

Beyond the exploration of km-scale RCMs or ESMs, model improvement should continue to be guided by process undertanding and the identification of forcings and feedbacks which remain particularly uncertain. Global metrics like climate sensitivity should not be the only focus given the on-going debate about the observed versus simulated pattern of global ocean warming [109–111] and the limited relevance of GWLs to narrow uncertainties in projected water cycle changes [118, 119]. A better understanding of changes in modes of variability and of potential tipping points is also policy-relevant but will not happen without further increasing the sampling of both structural and parametric modelling uncertainties and the size of initial condition ensembles, possibly with the help of machine-learning or ensemble boosting methods [120].

Moreover, the results should be communicated carefully given the media's tendency to pay more attention to extreme results, hence confusing the key messages of IPCC. Bridging the gap between the production and use of climate information may also benefit from considering climate change just as one among many other factors [121–123]. The complexity of local situations can be addressed by expressing climate knowledge in a conditional form, such as the use of physical climate storylines [124, 125]. A strong benefit of this "bottom-up" approach (and of Bayesian reasoning more generally) is that the role of multiple factors can be explicitly quantified in a logically self-consistent manner. We also concur with Rodrigues and Shepherd [121] when they argue that it may be necessary to (re)discover the "*beauty of smallness*" in order "*to make climate information useable for adaptation*" and "*to empower local communities to make sense of their own situation*".

The debate on climate modelling is clearly influenced by non-epistemic values. Yet, there are still disagreements about the role that such values should play in natural sciences [126]. Some argue that non-epistemic values are important for addressing uncertainties [127]. Other claim that such values can lead to detrimental cognitive biases [128]. It is thus important to identify when it is legitimate to appeal to non-epistemic values in scientific decisions. Such values may be legitimate when they promote democratically endorsed epistemological and social aims of research. Whatever their decision is, climate scientists (including IPCC lead-authors) should be trained on these complex issues. Far from being an inconvenient truth or a pretext for climate inaction, modelling uncertainty should be considered as an additional lever for the rapid implementation of no-regret mitigation and adaptation policies.

Trust in climate science is fragile and will also increasingly rely on scientists' behaviour as much as on their publications and public recommendations. As geophysical scientists, it may be thus our duty to nudge the future of climate modelling in a more principled and rational manner than we had in the past. Like other sectors of activity, climate research must develop a more reflexive approach and think of more efficient and effective uses of the available computing resources. Unfortunately, this ethical debate is often biased for multiple reasons including myopic leadership, overconfidence, and a strong international competition in high-performance computing.

The forthcoming IPCC round is an opportunity to develop new pathways toward increased inclusivity and reciprocity in the methods and communication strategy. The panel could for instance partly decouple "*epistemic authority*" from "*scientific authority*", and imagine new forms of expert contribution [129]. It could also pay more attention to alternative solutions within WGII and WGIII, not limited by the mainstream technical or political prerequisites (e.g., focus on supply-side technology rather than demand-side solutions, focus on model resolution rather than projection reliability). Attention to the future should not only be paid to how visions of the future underpin modelling practices in the present, but also to how contextualized practices bring that future into the present [130]. Doing better rather than promising more [131] remains an underexplored although basic and potentially effective path towards realistic goals acceptable to the majority.

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